PRESIDENTIAL COMMISSION

on the Space Shuttle Challenger Accident

Volume II

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Report to the President

Volume II

By The

PRESIDENTIAL COMMISSION

on the Space Shuttle Challenger Accident

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Appendix E—Independent Test Team Report to the Commission

Independent Test Observer Team Report

to the

Presidential Commission

on the

Space Shuttle Challenger Accident

by

Mohan Aswani
Laddie E. Dufka
Eugene G. Haberman
Don E. Kennedy
Michael L. Marx
Wilbur W. Wells

May 27, 1986

I. Summary

The Independent Test Observer Team was appointed by the Commission to assist its Accident Analysis Panel in the investigation of the Space Shuttle Mission 51-L accident by determining if the tests and analyses being performed by the Marshall Space Flight Center (MSFC) and Morton Thiokol, Incorporated (MTI) were adequate to provide the information needed by the panel. This included assessing whether the right tests and analyses were being done, whether the resulting information was being properly interpreted, and whether the information was sufficient to evaluate all the joint leakage failure mechanisms that were considered.

We have found that, with the exception of analyzing for partial joint rupture from all sources of preexistent cracks, MSFC and MTI have done the appropriate tests and analyses and collected and used the information properly. This has been sufficient to identify several possible mechanisms which acting either singly or in combination can lead to a joint leak.

If it is necessary to obtain more information regarding the leakage mechanisms of the joint, we recommend that full-scale testing be performed. Some members of the team have made specific recommendations regarding additional full-scale testing. We believe further sub-scale tests will not provide additional insight because the scaling factors between sub-scale and full-scale O-rings and joints are not well established.

II. Organization and Responsibilities

A. *Charter*

The Independent Observer Team was formed by the Commission to review and evaluate the Solid Rocket Motor's (SRM) joint and O-ring tests and the analyses being conducted by MSFC and MTI. Our charter was to answer the following questions:

- Are the appropriate tests and analyses being done correctly?
- Are the results being interpreted reasonably?
- How do the analytical results compare to the appropriate test results?

The answers to these questions were reported to the Accident Analysis Panel of the Commission, led by Major General Donald Kutyna, and are part of this report.

B. *Organization*

The members of the team and their affiliations are:

Eugene G. Haberman (Chairman)	Air Force Rocket Propulsion Laboratory
Mohan Aswani	The Aerospace Corporation
Laddie E. Dufka	The Aerospace Corporation
Don E. Kennedy	TRW
Michael L. Marx	National Transportation Safety Board
Wilbur W. Wells	Air Force Rocket Propulsion Laboratory

C. *Approach*

The team took a step-by-step approach to observing the tests and analyses being performed. The initial steps were an overview of the activities at MTI and MSFC and a review of how each possible leak mechanism presented by NASA related to the SRM joint and O-ring was supported by specific tests and analyses. We then looked at each test and analysis to assess its objectives, approaches, and results; the interpretation of these results and the conclusions drawn; the relationship between specific tests and analyses; and the adequacy of the information provided to evaluate the proposed leakage mechanisms. Finally we summarized our observations, reached conclusions and made recommendations to the Commission's Accident Analysis Panel.

Throughout the process members of the group made comments on the testing and analyses to the people involved. As a result, several changes were made, such as including grease in the O-ring resiliency tests (since the O-rings in the joint use grease), turning on the instruments during assembly of the referee joint to determine clevis leg deflection caused by placing the shims during assembly, and conducting 70-pound motor tests with undamaged O-rings.

At the midway point, we briefed senior MSFC members of the NASA Task Force Failure Analysis Team. Before preparing our final report, we briefed our observations and concerns to members of the Commission's Accident Analysis Panel and NASA's Task Force. We subsequently held detailed discussions with senior NASA personnel to resolve outstanding issues and to further discuss our observations, concerns, and recommendations.

III. Tests Evaluation

Tests conducted at both MSFC and at MTI in support of the STS 51-L accident investigation fall into the following categories:

A. *Basic Material Characterization*

The basic material characterization tests included O-ring properties characterization and joint material burning tests. Among these tests, resiliency characterization is by far the most comprehensive test, and the results clearly indicated the slow rebound response of O-rings at cold temperatures. The test results, therefore, support the O-ring actuation time delayed by the low temperature failure mechanism. The O-rings were also tested for the presence of defects and inclusions, and the results indicated their influence on the resiliency was minor. The joint material burning test was strictly qualitative and indicated the potential sources of black smoke. An additional observation was that white or gray smoke could turn black in the presence of oxygen.

Several areas of uncertainty relative to O-ring quality became apparent during this review. Splicing is carried out by a proprietary process, which precludes positive control to assure that changes that may require requalification are not introduced without approval by the customer. There is no requirement in the controlling documents that precludes splicing in a permanent twist that could distort the O-ring in its groove, nor is there an inspection procedure at MTI to detect a built-in twist.

Inspection of O-rings for inclusions has revealed high density metallic slivers and particles of iron oxide, silica, and calcium salts. Acceptance specification STW-7-2875 prohibits acceptance of hard white inclusions over 0.010-inch diameter, all visible black inclusions, and metallic inclusions of any size.

In one instance, traceability of one group of O-rings to the parent material's source and lot was completely lost by the supplier. Parts or materials of unknown pedigree therefore apparently were accepted for critical application.

B. *Cold Flow to Characterize Joint Performance*

In an attempt to characterize joint performance, several tests were carried out. Among these, the most significant tests were the O-Ring Blow-by Dynamic Test, the Discrete Increment Piston Cone Test, and the Ice in Joint Test. The O-Ring Blow-by Dynamic Test simulated the full-scale joint rotation, pressurization rate, and O-ring cross section (0.280-inch diameter) but was sub-scale with respect to the diameter of the joint. The results provided information about the influence of cold temperature, of initial squeeze, and of gap opening on the sealing capability of the joint and effectively used resiliency data to predict the leakage. They showed that low temperature and high squeeze consistently resulted in leakage, thus supporting O-ring seal failure mechanisms relating to low-temperature and high-squeeze effects. The Ice in Joint Test qualitatively demonstrated that the secondary O-ring could be pushed off its seat, thereby preventing it from sealing properly.

Putty installation into the small diameter full cross section joint used in the MTI Dynamic Vacuum Putty Extrusion Test appeared to be nonrepresentative of the full-scale joint. Applying putty layers into a small diameter restricted area, as compared to a large diameter (virtually straight) annulus, could create different putty functional characteristics. However, the results indicated that joint assembly could create black blowholes in the putty and that cold putty (30°) without blowholes could significantly delay pressurization of the primary O-ring cavity.

The other tests in this category, such as Putty Blow Through, provided qualitative indications further substantiating that putty could hold pressure off the primary O-ring. The colder the temperature, the longer blow through was delayed, possibly holding pressure off the primary O-ring long enough for joint rotation to occur. The O-ring Leak Port Integrity Test showed that leakage from this port was highly unlikely.

C. *Full-Scale Joint Simulation*

MTI has completed two phases of a three-phase test series designed to characterize the behavior of the clevis joint. The objective of the tests was to provide reliable displacement data for a typical lightweight joint under a constant internal pressure. The gap opening was compared with an analytical model, and the comparison was reasonable. It is our observation that this setup can be used to conduct several more tests to fully characterize the clevis joint and further validate the model.

The "Short Stack" full-diameter abbreviated segment apparatus was used to determine the influence of ice in the joint and its effect on the spreading of the clevis. The deflections measured were very small, which indicated that ice would not appreciably distort the joint.

D. *Hot-Firing Environmental Simulation*

The 5-inch-diameter hot-firing motor tests were conducted to get preliminary data for O-ring response to various defects and to develop design data for the 70-pound (propellant) hot-firing motor. Hence, while the motor operated at high-pressure and high-temperature conditions it was configured with only one O-ring and did not represent the true motor geometry. Qualitative data indicated that an O-ring joint can sustain leakage without an immediate burn through.

The 70-pound motor was a test bed that used the full-size clevis joint cross section and a motor diameter of 10 inches with durations of up to 70 seconds. It did not allow for dynamic joint rotation and, therefore, tested only the static joint condition. The results indicated that a leaking joint could be plugged by aluminum oxide and other deposits in induced leak paths. There was considerable randomness in these results when burn through mechanism simulation was attempted. The results, however, showed that a slow leak in the joint could eventually result in burn through at the joint or that an initial leak could be plugged by combustion products.

E. *Assembly Damage*

The full-diameter "Short Stack" was used to conduct tests for possible O-ring damage produced during joint assembly. During these tests, the segments were purposely misaligned axially while being assembled. Results showed that even during extreme conditions, no appreciable damage to the O-rings was found. However, because of the short height of the segments, the configuration was considered too flexible to provide meaningful results. The degree of misalignment was also believed to be extreme relative to realistic stacking conditions.

A similar test conducted by MSFC on a small sector of the full-scale joint showed that slivers of metal could result from improper assembly of the segments when they are excessively out of round or when assembly techniques produce too much interference causing a flat-on-flat condition. Both the small sector and "Short Stack" assembly tests also showed that considerable O-ring stretching can occur during an out-of-axial alignment assembly. Overall, these tests indicated that improper or careless assembly could produce damage or contamination contributing to initial seal leaking in the joint.

IV. Analyses Evaluation

The following analyses were performed in support of the STS 51-L investigation:

A. *Structural Analyses of SRM Segments, Field Joints and Seals*

The loading environment for structural analyses was determined from telemetered data, flight event reconstruction, analyses, and measured natural environments. A number of finite element models ranging from 2-D axisymmetric to 3-D nonlinear were prepared to evaluate the dynamic effects of bending and shell

modes on field joint response, the effects of elastic propellant, the interaction of joint and pins, and O-ring response. The results of analyses performed by MSFC and MTI match very well with the "Referee Test" data. However, the comparison was made only for one case of constant internal pressure.

The O-ring response analysis, based on the assumption that the O-ring is made of a linear elastic material, has provided qualitative data regarding the sealing mechanism. The analyses indicate that too much compression in the O-ring is harmful. In that event, when the O-ring occupies almost the entire gland volume and touches gland walls, it may not actuate properly to provide an effective seal. The assumptions made in the model make the results valuable for qualitative purposes only. These results tend to support the contributing mechanism of maximum O-ring squeeze limiting pressure-assisted actuation of the seal coupled with low temperature limiting the O-ring's capability to follow the sealing surface.

The fracture mechanics analyses conducted at MSFC, with respect to joint rupture due to mating loads and membrane rupture resulting from in-flight stresses showed that case rupture due to assembly and in-flight membrane rupture were unlikely. There is, however, a need to carefully examine the stresses in the clevis joint due to residual stress and induced loading, including mating, to adequately determine whether the joint could partially rupture from an undetected preexistent crack.

B. *Flow and Thermal Analyses*

Flow and thermal analyses were performed by MSFC in an attempt to explain the transition of the puff of smoke observed at 0.668 seconds into a hot jet at 58 seconds. The three scenarios considered were (1) the initial leak at liftoff continues throughout the 0 to 58-second period, limited by the deposit of aluminum and other debris; (2) the initial leak at liftoff continues throughout the 0 to 58-second period, limited by alumina and/or insulation and putty deposits, and at 58 seconds the blockage breaks open due to vibrations or closing of the joint resulting in burn through; and (3) the initial leak at liftoff does not continue past 5 to 6 seconds, and the leakage is sealed by alumina and/or insulation and putty debris, and at 58 seconds excessive vibrations or joint motions break the alumina deposit and cause rapid burn through. The analyses conducted thus far have not been able to favor one scenario over the other.

Additional flow and thermal analysis was conducted to determine the effect of inhibitor flaws and whether a debond between the propellant and the insulation could result in case or joint burn through at the appropriate time. Inhibitor flaws and debonds on both the upper and lower segments were analyzed, and the results indicated that burn through was not likely at the time and place it is believed to have occurred.

V. Conclusions

The review of Tests and Analyses conducted at MSFC and MTI led us to the following conclusions:

1. Inadequate quality control procedures for determining O-ring quality was indicated.
2. Insufficient analysis was performed for partial joint rupture emanating from all sources of preexistent cracks.
3. Adequate analyses and tests have been conducted to indicate that SRM inhibitor flaws, propellant debonds adjacent to the joint, leak check port leaks, and case membrane rupture from a preexisting crack are unlikely sources for burn through in the SRM.
4. Tests and analyses performed indicated that putty holding pressure, thereby delaying O-ring pressurization; low temperature adversely affecting O-ring resiliency; ice unseating the secondary O-ring; case diameter mismatch, resulting in near metal-to-metal contact, producing excessive squeeze that delays or prevents pressure-assisted actuation of the O-ring; and assembly damage could contribute to seal leakage.
5. Testing and analysis were performed which only approximate the operation of the full-scale joint and possible leaking mechanisms. Therefore, some caution is needed in projecting the operation of small-scale tests to full-scale hardware. In fact, it is apparent the operation of the full-scale joint and its leakage mechanisms is not fully understood.
6. Tests appear to support that a slow leak or a leak which becomes plugged by combustion products and soot can occur. Analysis indicates that a delay burn through is possible as a result of a slow leak or a leak that stops and later resumes.
7. Tests and analyses need further correlation.
8. In general, the results of the tests and analyses performed were interpreted properly, and the data was used correctly.

VI. Recommendations

1. If it is necessary to obtain more information regarding the leakage mechanisms of the SRM joint, we recommend that full-scale, full-diameter testing of the SRM joint be performed.
2. A more in-depth analysis for partial joint rupture emanating from all sources of preexistent cracking in the joint should be done.
3. Better O-ring quality control is needed, especially in the areas of avoiding twist in splicing, inspecting for inclusions, and pedigree.
4. Correlation of analyses and test results should continue.

VII. Additional Comments

Several members of the team (Haberman, Kennedy, and Wells) have strong recommendations for what should be included in additional tests. The remaining members of the team (Aswani, Dufka, and Marx) believe that specific test recommendations are not warranted and should not be included in this report.

From Haberman, Kennedy, and Wells:

Additional full-scale, full-diameter tests are recommended to provide increased understanding of how the SRM joint operates if it is necessary to further define joint operation and its leakage mechanisms.

The joint's operating environment should be simulated as accurately as possible during testing and should include consideration of external loads (due to "twang," External Tank attach struts, aerodynamic forces, etc.); internal loads (due to motor pressure, pressurization rate, thrust, etc.); temperature; water or ice in the joint; variations in hardware dimensions (i.e., O-ring dimensions, seal gap, segment ovality, inhibitor gap, repaired sealing surfaces, etc.); and putty variations (as affected by aging under representative temperature and humidity conditions, joint rotation, inhibitor gap, leak check pressurization, etc.). Many of these variables could be evaluated adequately in cold-gas pressurization tests with the MTI Short Stack and Referee Test hardware. The Short Stack could be used for assembly and O-ring leak-check tests to determine when and where back blowholes occur. It could also be used to evaluate the initial response of putty and O-rings before joint rotation. The Referee Test hardware, which is already well-instrumented, could be used for cold-gas pressurization tests that should include the effects of joint rotation water/ice in the joint, dimensional/fit variations, external loads, as well as temperature and putty conditions.

Critical points of interest in these tests are how the primary O-ring seal moves and seals as the joint rotates open under the influence of internal motor pressure and how O-ring performance is affected by the above variables. An important question, not answerable in sub-scale tests is, "Will the full-scale O-ring move and seal if part of it starts to do so?" This is important because the compression of the O-ring (which is a critical factor in O-

ring sealing, especially at low temperatures) is not uniform around the full-scale joint.

We also recommend that further full-scale tests be done to characterize SRM joint performance under hot-firing conditions to assess the viability of the slow leak and the leak/stop-leak/leak scenarios as explanations for the STS 51-L SRM joint failure. The joint environmental simulation hardware could be used for these tests; however, a minimum duration of 5 seconds should be considered. Specific test variables should be selected based on the results of the already completed sub-scale tests and the full-scale tests recommended above.

Appendix F—Personal Observations on Reliability of Shuttle

by R. P. Feynman.

It appears that there are enormous differences of opinion as to the probability of a failure with loss of vehicle and of human life. The estimates range from roughly 1 in 100 to 1 in 100,000. The higher figures come from working engineers, and the very low figures from management. What are the causes and consequences of this lack of agreement? Since 1 part in 100,000 would imply that one could put a Shuttle up each day for 300 years expecting to lose only one, we could more properly ask "What is the cause of management's fantastic faith in the machinery?"

We have also found that certification criteria used in Flight Readiness Reviews often develop a gradually decreasing strictness. The argument that the same risk was flown before without failure is often accepted as an argument for the safety of accepting it again. Because of this, obvious weaknesses are accepted again and again, sometimes without a sufficiently serious attempt to remedy them, or to delay a flight because of their continued presence.

There are several sources of information. There are published criteria for certification, including a history of modifications in the form of waivers and deviations. In addition, the records of the Flight Readiness Reviews for each flight document the arguments used to accept the risks of the flight. Information was obtained from the direct testimony and the reports of the range safety officer, Louis J. Ullian, with respect to the history of success of solid fuel rockets. There was a further study by him (as chairman of the launch abort safety panel (LASP)) in an attempt to determine the risks involved in possible accidents leading to radioactive contamination from attempting to fly a plutonium power supply (RTG) for future planetary missions. The NASA study of the same question is also available. For the history of the Space Shuttle Main Engines, interviews with management and engineers at Marshall, and informal interviews with engineers at Rocketdyne were made. An independent (Cal Tech) mechanical engineer who consulted for NASA about engines was also interviewed informally. A visit to Johnson was made to gather information on the reliability of the avionics (computers, sensors, and effectors). Finally there is a report "A Review of Certification Practices Potentially Applicable to Man-rated Reusable Rocket Engines," prepared at the Jet Propulsion Laboratory by N. Moore, et al., in February, 1986, for NASA Headquarters, Office of Space Flight. It deals with the methods used by the FAA and the military to certify their gas turbine and rocket engines. These authors were also interviewed informally.

Solid Fuel Rockets (SRB)

An estimate of the reliability of solid fuel rockets was made by the range safety officer, by studying the experience of all previous rocket flights. Out of a total of nearly 2,900 flights, 121 failed (1 in 25). This includes, however, what may be called, early errors, rockets flown for the first few times in which design errors are discovered and fixed. A more reasonable figure for the mature rockets might be 1 in 50. With special care in the selection of the parts and in inspection, a figure of below 1 in 100 might be achieved but 1 in 1,000 is probably not attainable with today's technology. (Since there are two rockets on the Shuttle, these rocket failure rates must be doubled to get Shuttle failure rates from Solid Rocket Booster failure.)

NASA officials argue that the figure is much lower. They point out that these figures are for unmanned rockets but since the Shuttle is a manned vehicle "the probability of mission success is necessarily very close to 1.0." It is not very clear what this phrase means. Does it mean it is close to 1 or that it ought to be close to 1? They go on to explain "Historically this extremely high degree of mission success has given rise to a difference in philosophy between manned space flight programs and unmanned programs; i.e., numerical probability usage versus engineering judgment." (These quotations are from "Space Shuttle Data for Planetary Mission RTG Safety Analysis," pages 3-1, 3-2, February 15, 1985, NASA, JSC.) It is true that if the probability of failure was as low as 1 in 100,000 it would take an inordinate number of tests to determine it (for you would get nothing but a string of perfect flights from which no precise figure, other than that the probability is likely less than the number of such flights in the string so far). But, if the real probability is not so small, flights would show troubles, near failures, and possibly actual failures with a reasonable number of trials, and standard statistical methods could give a reasonable estimate. In fact, previous NASA experience had shown, on occasion, just such difficulties, near accidents, and accidents, all giving warning that the probability of flight failure was not so very small. The inconsistency of the argument not to determine reliability through historical experience, as the range safety officer did, is that NASA also appeals to history, beginning "Historically this high degree of mission success . . . ." Finally, if we are to replace standard numerical probability usage with engineering judgment, why do we find such an enormous disparity between the management estimate and the judgment of the engineers? It would appear that, for whatever purpose, be it for internal or external consumption, the management of NASA exaggerates the reliability of its product, to the point of fantasy.

The history of the certification and Flight Readiness Reviews will not be repeated here. (See other part of Commission reports.) The phenomenon of accepting for flight, seals that had shown erosion and blow-by in previous flights, is very clear. The Challenger flight is an excellent example. There are several references to flights, that had gone before. The acceptance and success of these flights is taken as evidence of safety. But erosion and blow-by are not what the design expected. They are warnings that something is wrong. The equipment is not operating as expected, and therefore there is a danger that it can operate with even wider deviations in this unexpected and not thoroughly understood way. The fact that this danger did not lead to a catastrophe before is no guarantee that it will not the next time, unless it is completely understood. When playing Russian roulette the fact that the first shot got off safely is little comfort for the next. The origin and consequences of the erosion and blow-by were not understood. They did not occur equally on all flights and all joints; sometimes more, and sometimes less. Why not sometime, when whatever conditions determined it were right, still more, leading to catastrophe?

In spite of these variations from case to case, officials behaved as if they understood it, giving apparently logical arguments to each other often depending on the "success" of previous flights. For example, in determining if flight 51-L was safe to fly in the face of ring erosion in flight 51-C, it was noted that the erosion depth was only one-third of the radius. It had been noted in an

experiment cutting the ring that cutting it as deep as one radius was necessary before the ring failed. Instead of being very concerned that variations of poorly understood conditions might reasonably create a deeper erosion this time, it was asserted, there was "a safety factor of three." This is a strange use of the engineer's term "safety factor." If a bridge is built to withstand a certain load without the beams permanently deforming, cracking, or breaking, it may be designed for the materials used to actually stand up under three times the load. This "safety factor" is to allow for uncertain excesses of load, or unknown extra loads, or weaknesses in the material that might have unexpected flaws, etc. If now the expected load comes on to the new bridge and a crack appears in a beam, this is a failure of the design. There was no safety factor at all; even though the bridge did not actually collapse because the crack only went one-third of the way through the beam. The O-rings of the Solid Rocket Boosters were not designed to erode. Erosion was a clue that something was wrong. Erosion was not something from which safety can be inferred.

There was no way, without full understanding, that one could have confidence that conditions the next time might not produce erosion three times more severe than the time before. Nevertheless, officials fooled themselves into thinking they had such understanding and confidence, in spite of the peculiar variations from case to case. A mathematical model was made to calculate erosion. This was a model based not on physical understanding but on empirical curve fitting. To be more detailed, it was supposed a stream of hot gas impinged on the O-ring material, and the heat was determined at the point of stagnation (so far, with reasonable physical, thermodynamic laws). But to determine how much rubber eroded it was assumed this depended only on this heat by a formula suggested by data on a similar material. A logarithmic plot suggested a straight line, so it was supposed that the erosion varied as the .58 power of the heat, the .58 being determined by a nearest fit. At any rate, adjusting some other numbers, it was determined that the model agreed with the erosion (to depth of one-third the radius of the ring). There is nothing much so wrong with this as believing the answer! Uncertainties appear everywhere. How strong the gas stream might be was unpredictable, it depended on holes formed in the putty. Blow-by showed that the ring might fail even though not, or only partially eroded through. The empirical formula was known to be uncertain, for it did not go directly through the very data points by which it was determined. There were a cloud of points some twice above, and some twice below the fitted curve, so erosions twice predicted were reasonable from that cause alone. Similar uncertainties surrounded the other constants in the formula, etc., etc. When using a mathematical model careful attention must be given to uncertainties in the model.

Liquid Fuel Engine (SSME)

During the flight of 51-L the three Space Shuttle Main Engines all worked perfectly, even, at the last moment, beginning to shut down the engines as the fuel supply began to fail. The question arises, however, as to whether, had it failed, and we were to investigate it in as much detail as we did the Solid Rocket Booster, we would find a similar lack of attention to faults and a deteriorating reliability. In other words, were the organization weaknesses that contributed to the accident confined to the Solid Rocket Booster sector or were they a more general characteristic of NASA? To that end the Space Shuttle Main Engines and the avionics were both investigated. No similar study of the Orbiter, or the External Tank was made.

The engine is a much more complicated structure than the Solid Rocket Booster, and a great deal more detailed engineering goes into it. Generally, the engineering seems to be of high quality and apparently considerable attention is paid to deficiencies and faults found in operation.

The usual way that such engines are designed (for military or civilian aircraft) may be called the component system, or bottom-up design. First it is necessary to thoroughly understand the properties and limitations of the materials to be used (for turbine blades, for example), and tests are begun in experimental rigs to determine those. With this knowledge larger component parts (such as bearings) are designed and tested individually. As deficiencies and design errors are noted they are corrected and verified with further testing. Since one tests only parts at a time these tests and modifications are not overly expensive. Finally one works up to the final design of the entire engine, to the necessary specifications. There is a good chance, by this time that the engine will generally succeed, or that any failures are easily isolated and analyzed because the failure modes, limitations of materials, etc., are so well understood. There is a very good chance that the modifications to the engine to get around the final difficulties are not very hard to make, for most of the serious problems have already been discovered and dealt with in the earlier, less expensive, stages of the process.

The Space Shuttle Main Engine was handled in a different manner, top down, we might say. The engine was designed and put together all at once with relatively little detailed preliminary study of the material and components. Then when troubles are found in the bearings, turbine blades, coolant pipes, etc., it is more expensive and difficult to discover the causes and make changes. For example, cracks have been found in the turbine blades of the high pressure oxygen turbopump. Are they caused by flaws in the material, the effect of the oxygen atmosphere on properties of the material, the thermal stresses of startup or shutdown, the vibration and stresses of steady running, or mainly at some resonance at certain speeds, etc.? How long can we run from crack initiation to crack failure, and how does this depend on power level? Using the completed engine as a test bed to resolve such questions is extremely expensive. One does not wish to lose entire engines in order to find out where and how failure occurs. Yet, an accurate knowledge of this information is essential to acquire a confidence in the engine reliability in use. Without detailed understanding, confidence cannot be attained.

A further disadvantage of the top-down method is that, if an understanding of a fault is obtained, a simple fix, such as a new shape for the turbine housing, may be impossible to implement without a redesign of the entire engine.

The Space Shuttle Main Engine is a very remarkable machine. It has a greater ratio of thrust to weight than any previous engine. It is built at the edge of, or outside of, previous engineering experience. Therefore, as expected, many different kinds of flaws and difficulties have turned up. Because, unfortunately, it was built in the top-down manner, they are difficult to find and to fix. The design aim of a lifetime of 55 mission equivalent firings (27,000 seconds of operation, either in a mission of 500 seconds, or on a test stand) has not been obtained. The engine now requires very frequent maintenance and replacement of important parts, such as turbopumps, bearings, sheet metal housings, etc. The high-pressure fuel turbopump had to be replaced every three or four mission equivalents (although that may have been fixed, now) and the high-pressure oxygen turbopump every five or six. This is at most ten percent of the original specification. But our main concern here is the determination of reliability.

In a total of about 250,000 seconds of operation, the engines have failed seriously perhaps 16 times. Engineering pays close attention to these failings and tries to remedy them as quickly as possible. This it does by test studies on special rigs experimentally designed for the flaw in question, by careful inspection of the engine for suggestive clues (like cracks), and by considerable study and analysis. In this way, in spite of the difficulties of top-down design, through hard work, many of the problems have apparently been solved.

A list of some of the problems follows. Those followed by an asterisk are probably solved;

- Turbine blade cracks in high-pressure fuel turbopumps (HPFTP). (May have been solved.)
- Turbine blade cracks in high-pressure oxygen turbopumps (HPOTP).
- Augmented Spark Igniter (ASI) line rupture.*
- Purge check valve failure.*
- ASI chamber erosion.*
- HPFTP turbine sheet metal cracking.
- HPFTP coolant liner failure.*
- Main combustion chamber outlet elbow failure.*
- Main combustion chamber inlet elbow weld offset.*
- HPOTP subsynchronous whirl.*
- Flight acceleration safety cutoff system (partial failure in a redundant system).*
- Bearing spalling (partially solved).
- A vibration at 4,000 Hertz making some engines inoperable, etc.

Many of these solved problems are the early difficulties of a new design, for 13 of them occurred in the first 125,000 seconds and only three in the second 125,000 seconds. Naturally, one can never be sure that all the bugs are out, and, for some, the fix may not have addressed the true cause. Thus, it is not unreasonable to guess there may be at least one surprise in the next 250,000 seconds, a probability of 1/500 per engine per mission. On a mission there are three engines, but some accidents would possibly be contained, and only affect one engine. The system can abort with only two engines. Therefore let us say that the unknown surprises do not, even of themselves, permit us to guess that the probability of mission failure due to the Space Shuttle Main Engine is less than 1/500. To this we must add the chance of failure from known, but as yet unsolved, problems (introduced by asterisk in the list above). These we discuss below. (Engineers at Rocketdyne, the manufacturer, estimate the total probability as 1/10,000. Engineers at Marshall estimate it as 1/300, while NASA management, to whom these engineers report, claims it is 1/100,000. An independent engineer consulting for NASA thought 1 or 2 per 100 a reasonable estimate.)

The history of the certification principles for these engines is confusing and difficult to explain. Initially the rule seems to have been that two sample engines must each have had twice the time operating without failure, as the operating time of the engine to be certified (rule of 2x). At least that is the FAA practice, and NASA seems to have adopted it, originally expecting the certified time to be 10 missions (hence 20 missions for each sample). Obviously the best engines to use for comparison would be those of greatest total (flight plus test) operating time—the so-called "fleet leaders." But what if a third sample and several others fail in a short time? Surely we will not be safe because two were unusual in lasting longer. The short time might be more representative of the real possibilities, and in the spirit of the safety factor of 2, we should only operate at half the time of the short-lived samples.

The slow shift toward decreasing safety factor can be seen in many examples. We take that of the HPFTP turbine blades. First of all the idea of testing an entire engine was abandoned. Each engine number has had many important parts (like the turbopumps themselves) replaced at frequent intervals, so that the rule must be shifted from engines to components. We accept an HPFTP for a certification time if two samples have each run successfully for twice that time (and of course, as a practical matter, no longer insisting that this time be as large as 10 missions). But what is "successfully"? The FAA calls a turbine blade crack a failure, in order, in practice, to really provide a safety factor greater than 2. There is some time that an engine can run between the time a crack originally starts until the time it has grown large enough to fracture. (The FAA is contemplating new rules that take this extra safety time into account, but only if it is very carefully analyzed through known models within a known range of experience and with materials thoroughly tested. None of these conditions apply to the Space Shuttle Main Engine.

Cracks were found in many second stage HPFTP turbine blades. In one case three were found after 1,900 seconds, while in another they were not found after 4,200 seconds, although usually these longer runs showed cracks. To follow this story further we shall have to realize that the stress depends a great deal on the power level. The Challenger flight was to be at, and previous flights had been at, a power level called 104% of rated power level during most of time the engines were operating. Judging from some material data it is supposed that at the level 104% of rated power level, the time to crack is about twice that at 109% or full power level (FPL). Future flights were at this level because of heavier payloads, and many tests were made at this level. Therefore dividing time at 104% by two, we obtain units called equivalent full power level (EFPL). (Obviously, some uncertainty is introduced by that, but it has not been studied.) The earliest cracks mentioned above occurred at 1,375 EFPL.

Now the certification rule becomes "limit all second stage blades to a maximum of 1,375 seconds EFPL." If one objects that the factor of 2 is lost it is pointed out that the one turbine ran for 3,800 seconds EFPL without cracks, and half of this is 1,900 so we are being more conservative. We have fooled ourselves in three ways. First we have only one sample, and it is not the fleet leader, for the other two samples of 3,800 or more seconds had 17 cracked blades between them. (There are 59 blades in the engine.) Next we have abandoned the 2x rule and substituted equal time. And finally, 1,375 is where we did see a crack. We can say that no crack had been found below 1,375, but the last time we looked and saw no cracks was 1,100 seconds EFPL. We do not know when the crack formed between these times, for example cracks may have formed at 1,150 seconds EFPL. (Approximately ⅗ of the blade sets tested in excess of 1,375 seconds EFPL had cracks. Some recent experiments have, indeed, shown cracks as early as 1,150 seconds.) It was important to keep the number high, for the Challenger was to fly an engine very close to the limit by the time the flight was over.

Finally it is claimed that the criteria are not abandoned, and the system is safe, by giving up the FAA convention that there should be no cracks, and considering only a completely fractured blade a failure. With this definition no engine has yet failed. The idea is that since there is sufficient time for a crack to grow to fracture we can insure that all is safe by inspecting all blades for cracks. If they are found, replace them, and if none are found we have enough time for a safe mission. This makes the crack problem not a flight safety problem, but merely a maintenance problem.

This may in fact be true. But how well do we know that cracks always grow slowly enough that no fracture can occur in a mission? Three engines have run for long times with a few cracked blades (about 3,000 seconds EFPL) with no blades broken off.

But a fix for this cracking may have been found. By changing the blade shape, shot-peening the surface, and covering with insulation to exclude thermal shock, the blades have not cracked so far.

A very similar story appears in the history of certification of the HPOTP, but we shall not give the details here.

It is evident, in summary, that the Flight Readiness Reviews and certification rules show a deterioration for some of the problems of the Space Shuttle Main Engine that is closely analogous to the deterioration seen in the rules for the Solid Rocket Booster.

Avionics

By "avionics" is meant the computer system on the Orbiter as well as its input sensors and output actuators. At first we will restrict ourselves to the computers proper and not be concerned with the reliability of the input information from the sensors of

temperature, pressure, etc., nor with whether the computer output is faithfully followed by the actuators of rocket firings, mechanical controls, displays to astronauts, etc.

The computing system is very elaborate, having over 250,000 lines of code. It is responsible, among many other things, for the automatic control of the entire ascent to orbit, and for the descent until well into the atmosphere (below Mach 1) once one button is pushed deciding the landing site desired. It would be possible to make the entire landing automatically (except that the landing gear lowering signal is expressly left out of computer control, and must be provided by the pilot, ostensibly for safety reasons) but such an entirely automatic landing is probably not as safe as a pilot controlled landing. During orbital flight it is used in the control of payloads, in displaying information to the astronauts, and the exchange of information to the ground. It is evident that the safety of flight requires guaranteed accuracy of this elaborate system of computer hardware and software.

In brief, the hardware reliability is ensured by having four essentially independent identical computer systems. Where possible each sensor also has multiple copies, usually four, and each copy feeds all four of the computer lines. If the inputs from the sensors disagree depending on circumstances certain averages, or a majority selection is used as the effective input. The algorithm used by each of the four computers is exactly the same, so their inputs (since each sees all copies of the sensors) are the same. Therefore at each step the results in each computer should be identical. From time to time they are compared, but because they might operate at slightly different speeds a system of stopping and waiting at specified times is instituted before each comparison is made. If one of the computers disagrees, or is too late in having its answer ready, the three which do agree are assumed to be correct and the errant computer is taken completely out of the system. If, now, another computer fails, as judged by the agreement of the other two, it is taken out of the system, and the rest of the flight canceled, and descent to the landing site is instituted, controlled by the two remaining computers. It is seen that this is a redundant system since the failure of only one computer does not affect the mission. Finally, as an extra feature of safety, there is a fifth independent computer, whose memory is loaded with only the programs for ascent and descent, and which is capable of controlling the descent if there is a failure of more than two of the computers of the main line of four.

There is not enough room in the memory of the main line computers for all the programs of ascent, descent, and payload programs in flight, so the memory is loaded about four times from tapes, by the astronauts.

Because of the enormous effort required to replace the software for such an elaborate system, and for checking a new system out, no change has been made in the hardware since the system began about fifteen years ago. The actual hardware is obsolete; for example, the memories are of the old ferrite core type. It is becoming more difficult to find manufacturers to supply such old-fashioned computers reliably and of high quality. Modern computers are very much more reliable, can run much faster, simplifying circuits, and allowing more to be done, and would not require so much loading of memory, for their memories are much larger.

The software is checked very carefully in a bottom-up fashion. First, each new line of code is checked, then sections of codes or modules with special function are verified. The scope is increased step by step until the new changes are incorporated into a complete system and checked. This complete output is considered the final product, newly released. But completely independently there is an independent verification group, that takes an adversary attitude to the software development group, and tests and verifies the software as if it were a customer of a delivered product. There is additional verification in using the new programs in simulators, etc. A discovery of an error during the verification testing is considered very serious, and its origin studied very carefully to avoid such mistakes in the future. Such unexpected errors have been found only about six times in all the programming and program changing (for new or altered payloads) that has been done. The principle that is followed is that all the verification is not an aspect of program safety, it is merely a test of that safety, in a non-catastrophic verification. Flight safety is to be judged solely on how well the programs do in the verification tests. A failure here generates considerable concern.

To summarize then, the computer software checking system and attitude is of highest quality. There appears to be no process of gradually fooling oneself while degrading standards so characteristic of the Solid Rocket Booster or Space Shuttle Main Engine safety systems. To be sure, there have been recent suggestions by management to curtail such elaborate and expensive tests as being unnecessary at this late date in Shuttle history. This must be resisted for it does not appreciate the mutual subtle influences, and sources of error generated by even small changes on one part of a program on another. There are perpetual requests for changes as new payloads and new demands and modifications are suggested by the users. Changes are expensive because they require extensive testing. The proper way to save money is to curtail the number of requested changes, not the quality of testing for each.

One might add that the elaborate system could be very much improved by more modern hardware and programming techniques. Any outside competition would have all the advantages of starting over, and whether that is a good idea for NASA now should be carefully considered.

Finally, returning to the sensors and actuators of the avionics system, we find that the attitude to system failure and reliability is not nearly as good as for the computer system. For example, a difficulty was found with certain temperature sensors sometimes failing. Yet 18 months later the same sensors were still being used, still sometimes failing, until a launch had to be scrubbed because two of them failed at the same time. Even on a succeeding flight this unreliable sensor was used again. Again reaction control systems, the rocket jets used for reorienting and control in flight, still are somewhat unreliable. There is considerable redundancy, but a long history of failures, none of which has yet been extensive enough to seriously affect a flight. The action of the jets is checked by sensors, and, if they fail to fire the computers choose another jet to fire. But they are not designed to fail, and the problem should be solved.

Conclusions

If a reasonable launch schedule is to be maintained, engineering often cannot be done fast enough to keep up with the expectations of originally conservative certification criteria designed to guarantee a very safe vehicle. In these situations, subtly, and often with apparently logical arguments, the criteria are altered so that flights may still be certified in time. They therefore fly in a relatively unsafe condition, with a chance of failure of the order of a percent (it is difficult to be more accurate).

Official management, on the other hand, claims to believe the probability of failure is a thousand times less. One reason for this may be an attempt to assure the government of NASA perfection and success in order to ensure the supply of funds. The other may be that they sincerely believe it to be true, demonstrating an almost incredible lack of communication between themselves and their working engineers.

In any event this has had very unfortunate consequences, the most serious of which is to encourage ordinary citizens to fly in such a dangerous machine, as if it had attained the safety of an ordinary airliner. The astronauts, like test pilots, should know their risks, and we honor them for their courage. Who can doubt that McAuliffe was equally a person of great courage, who was closer to an awareness of the true risk than NASA management would have us believe?

Let us make recommendations to ensure that NASA officials deal in a world of reality in understanding technological weaknesses and imperfections well enough to be actively trying to eliminate them. They must live in reality in comparing the costs and utility of the Shuttle to other methods of entering space. And they must be realistic in making contracts, in estimating costs, and the difficulty of the projects. Only realistic flight schedules should be proposed, schedules that have a reasonable chance of being met. If in this way the government would not support them, then so be it. NASA owes it to the citizens from whom it asks support to be frank, honest, and informative, so that these citizens can make the wisest decisions for the use of their limited resources.

For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.

Appendix G—Human Factors Analysis

The Commission staff investigators reviewed the work schedules of NASA and contractor personnel involved in the launch processing of the Challenger at Kennedy and of the Marshall managers involved in the January 27th teleconference discussion of low temperature effects on the Solid Rocket Booster joint. The results of the review are presented herein. Although major accident investigations now include human factor analyses, the Commission avoided drawing specific conclusions regarding the effects of work schedules on work performance or management judgment. However, with the concurrence of NASA officials the Commission agreed that the results of the review should be included as an appendix to the Commission report. An evaluation by NASA of the consequences of work schedules should be conducted as part of its effort to reform its launch and operational procedures.

Workload Demands at Kennedy Space Center

The ground crews at Kennedy have final responsibility for physically preparing the Shuttle for launch. To meet the mission launch time requirements, the entire preparation sequence follows a strict schedule that imposes an around-the-clock work requirement on several large groups of workers including launch control center personnel.

While shiftwork is commonplace in many industrial settings, few can equal a Shuttle launch's potential for inducing pressure to work beyond reasonable overtime limits. Such workload pressure increases when launch rates are accelerated or when unanticipated delays are encountered in the launch schedule, especially within the last few days before lift off. Research has shown that when overtime becomes excessive, worker efficiency decreases and the potential for human error rises.[1]

Shiftwork, Overtime and Safety

The importance of shiftwork and overtime as safety issues is underscored by the variety of accidents and incidents which have been reported at Kennedy in recent years. The Lockheed Space Operations Company Incident/Error Review Board reviewed a total of 117 and 147 incidents (mishaps with property damage less than $25,000) during calendar years 1984 and 1985, respectively. Of these, 51.3 and 56.5 percent were attributable to some type of human error, including procedural deviations, miscommunications and safety violations.[2] There were also 12 reportable mishaps with property damage greater than $25,000 in 1984 and 24 in 1985.[3] The incident statistics, while revealing, underestimate the extent of the problem because some incidents never get reported.[4]

One potentially catastrophic human error occurred 4 minutes, 55 seconds before the scheduled launch of mission 61-C on January 6, 1986. According to a Lockheed Space Operations Company Incident Report, 18,000 pounds of liquid oxygen were inadvertently drained from the Shuttle External Tank due to operator error. Fortunately, the liquid oxygen flow dropped the main engine inlet temperature below the acceptable limit causing a launch hold, but only 31 seconds before lift off. As the report states, "Had the mission not been scrubbed, the ability of the Orbiter to reach defined orbit may have been significantly impacted."[5]

It wasn't until after the hold was called because of the temperature drop that anyone realized that liquid oxygen had been dumped. As Arnold Aldrich, Manager, National Space Transportation System, later commented, this loss of liquid oxygen "could have led to serious safety of flight consequences had the team elected to waive the SSME [Space Shuttle Main Engine] temperature redlines and proceed with the launch."[6] The investigation revealed that console operators in the launch control center at Kennedy had misinterpreted system error messages resulting from a failed microswitch on a replenishment valve. Consequently, instead of manually overriding an automatic sequencer and closing the next valve in the sequence, they pressed "Continue" and caused the vent and drain valves to open prematurely. The report cites operator fatigue as one of the major factors contributing to this incident. The operators had been on duty at the console for eleven hours during the third day of working 12-hour night (8:00 p.m. to 8:00 a.m.) shifts.

Excessive Shiftwork Pressures

There are over 5,000 contract workers engaged in Shuttle processing at Kennedy. These individuals are responsible for assembly, fueling, launch pad preparation and other pre-flight requirements. Mission 51-L was one of several missions they were processing during the three months preceding the accident on January 28, 1986. In January five aborts and two launches, of which three fell on Saturday, Sunday or Monday, resulted in an unusually high amount of overtime for these employees.[7]

During November, December and January, the average monthly overtime percentages for the various directorates at Kennedy rose significantly. Some were as high as 27.7 percent, and many were in the 20 to 26 percent range (48- to 50-hour weeks). During interviews both Robert Sieck, Director, Space Shuttle Operations, and David Owen, deputy program manager for Lockheed, have described 20 percent overtime as equivalent to a 48-hour or six-day week.[8] Such descriptions can be misleading because they are based on averages that include all workers including those with no overtime hours. Thus, while they provide a rough estimate of overtime trends, they do not address the distribution of overtime within the group. This is important because it is individual performance, not group performance, that affects the safety of the operation.

Consequently, Commission investigators analyzed 41,105 individual weekly timecard records for all 429 Morton Thiokol employees from October 6, 1985 to February 2, 1986, and for 2,451 Lockheed employees from October 26, 1985 to January 31, 1986. The Lockheed sample included all workers in the directorates that had the highest overtime percentages during the three-month period under examination (Process Planning and Control, Orbiter Processing Facility Operations, Launch Control Center Operations, Pad Operations, Facility Operations and Maintenance, and Reliability and Quality Assurance). The analysis of both sets of records was designed to permit comparison of the actual overtime hours with the guidelines of management.

Management Controls

Both Morton Thiokol and Lockheed Space Operations Company have management policies regulating employee overtime.[9] Each requires prior approval by the director for anyone working more than 20 hours, or 50 percent, overtime in one week; however, they differ in their regulation of successive workdays. Thiokol requires advance vice presidential approval for anyone working more than 13 consecutive days. Lockheed requires such approval for working more than six days in a week but has no formal policy governing more than six successive workdays if they

occur across a two-week span. Instead, some directorates have informal policies or guidelines that are used to plan shiftwork scheduling. Neither company has any policy that regulates the number of successive overtime days separate from that governing successive workdays.

The individual weekly labor records revealed that the 20-hour limitation was exceeded 480 times by Morton Thiokol employees during the 18 weeks examined. More important is the distribution of this high overtime throughout the workforce. Only 169 of the 429 workers shared these weeks. Thus, although the overall average number of high overtime weeks was only 1.12 per employee, it was 2.84 weeks for those actually affected and ranged up to seven weeks for some individuals. The amount of weekly overtime often substantially exceeded 20 hours. In fact, there were 35 instances of employees working 40 or more hours overtime in addition to their usual 40 standard work hours.[10]

The equivalent number of high overtime weeks for Lockheed employees was 2,512 during the 14 weeks examined. Again, only 1,013 of the 2,451 total employees were exposed to such high overtime, resulting in an overall average of 1.02 weeks per employee but an average of 2.48 weeks for those actually affected. The highest incidence occurred during the week of November 9 to 15, when 298 of the 2,403 employees (12.4%) exceeded the 20-hour limit. Some individuals exceeded the limit during as many as 11 of the 14 weeks, while others worked nine consecutive weeks in excess of 20 hours overtime. There were 114 instances of employees working 40 or more hours overtime in addition to 40 standard work hours, including two employees who each worked a total of 96 hours one week in January before the accident.[11] One of these individuals, a mechanical technician team leader, worked 60, 96.5, 94, and 80.8 hours per week in succession during the four weeks ending January 31, 1986.

Individual Workers

These levels of individual weekly overtime prompted a more focused analysis of the daily work hours for a selected sample of high overtime contract employees. The analysis was based on those time periods when the percent of overtime was unusually high and when processing of the Challenger Orbiter and Solid Rocket Boosters was taking place. The selection criteria were designed to include both those who worked several weeks of overtime in succession and those who worked an unusually high amount of overtime during any one week. The sample for Thiokol included all employees, a total of 48, who met the following criteria during the six weeks from November 3 to December 15, 1985:[12]

- Worked at least two weeks of 64 hours or more.
- Worked more than 40 hours for three consecutive weeks including two of at least 60 hours.
- Worked at least 75 hours during any week.

The Lockheed sample was based on more restrictive criteria in order to keep its size reasonable despite the much larger number of total employees:

- Worked at least two weeks of 64 hours or more during any three consecutive weeks.
- Worked at least 75 hours during any week.

These criteria were met by 239 Lockheed employees during the 13 weeks beginning October 26, 1985, and ending January 24, 1986. A final sample of 93 individuals was then assembled by combining all the workers who met the criteria in the three departments with the most cases.[13] Because a department's workload varies considerably each week depending on the current stage of Shuttle processing, each group of employees was examined only during the periods of peak overtime pressure for that department. These varied from seven to ten weeks extending from November 2, 1985 to January 24, 1986.

Three independent contributors to excessive overtime required examination:

- Consecutive workdays.
- Daily hours.
- Multiple shift changes.

The first two consequences were addressed together in the group analysis which follows. The third appeared to occur less extensively than the others and was therefore addressed separately on an individual case basis. Due to the sampling procedure, the results of the analysis reflect the upper extreme of the shiftwork continuum at Kennedy.

For the combined analysis the number of consecutive workdays was tallied separately for each group. The results are summarized in the following table. The mean number of consecutive workdays was calculated for all days, standard and overtime, and for overtime days only without any intervening standard eight-hour days or days off. The overtime results were further divided into increasingly longer workdays by two-hour intervals to better reflect the combination of working long hours several days in a row. The frequencies of occurrence of consecutive overtime days (i.e., two days or more) are also listed for each sample and overtime condition along with the maximum number of consecutive days worked by any one individual.

The left side of the table indicates that during this time both the Lockheed and Thiokol employees worked an average of seven to eight days in a row before a day off. Although only one employee in each group worked the highest number of consecutive days, 50 and 26 respectively, there were a considerable number who worked two weeks or more without a day off, especially at Lockheed. This distribution is readily apparent in Figure 1 which shows how often each company's employees worked more than six consecutive days. Separate frequencies of occurrence are plotted for increasingly longer work "weeks." The sharp drop-off seen in the Thiokol data after 12 days coincides with that company's policy limiting consecutive workdays to 13 or fewer and may reflect the effectiveness of that policy.

The right side of the table reveals the exposure of both groups to successive overtime workdays. The average number of consecutive workdays was computed for three categories of total daily hours: exceeding eight hours, equaling 10 or more hours, or equaling 12 or more hours. Thus, each succeeding category represents a more difficult work schedule. Within each company it is apparent that as the schedule becomes more difficult there is only a limited decrease in the exposure to continuous overtime days. Both the mean and the highest number of days change relatively little as the categories increase from 8 to 12 hours. Although dif-

Number of Consecutive Workdays at Kennedy Space Center: Selected High Overtime Employees

	ALL DAYS		OVERTIME DAYS ONLY								
	Consecutive Days		Consecutive Days > 8 Hours			Consecutive Days ≥ 10 Hours			Consecutive Days ≥ 12 Hours		
	Mean	Max	Mean	Max	Freq	Mean	Max	Freq	Mean	Max	Freq
Lockheed (N = 93)	7.36	50	4.62	15	451	4.56	14	447	4.62	14	180
Thiokol (N = 48)	7.97	26	4.26	13	113	4.12	9	112	3.95	7	108

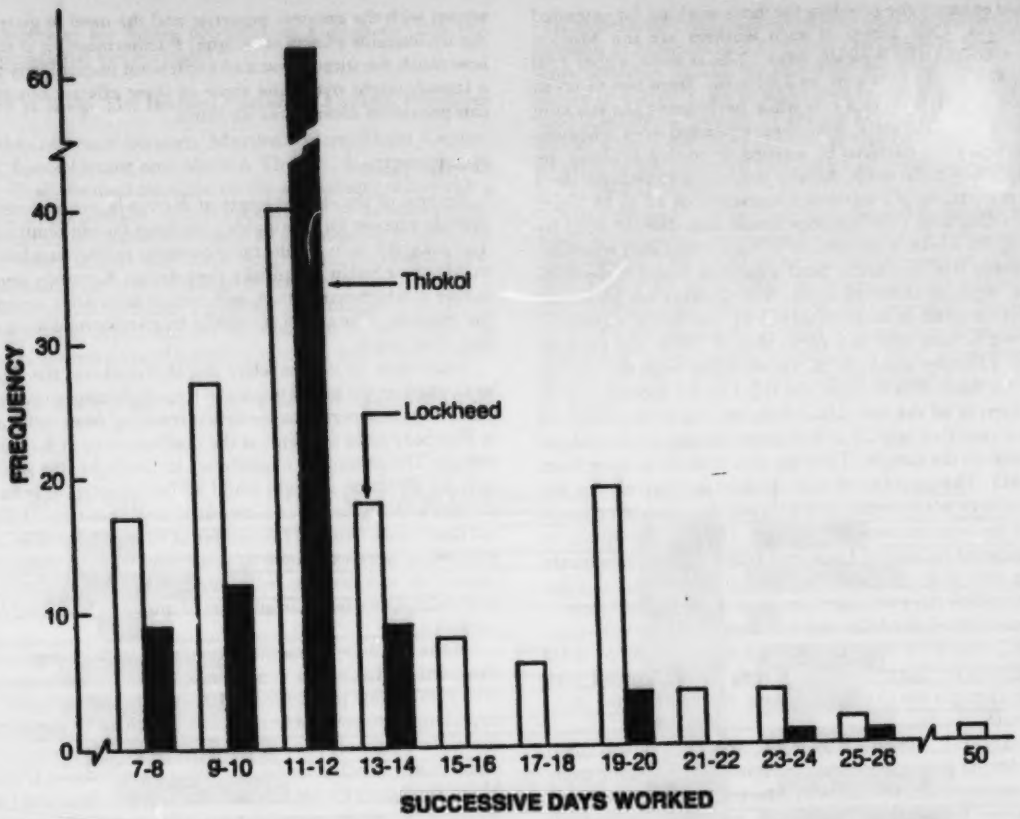

Figure 1—Incidence of more than six consecutive workdays among a group of Lockheed (N = 93) and Thiokol (N = 48) shiftworkers at Kennedy Space Center. Time period of sample varies from seven to ten weeks extending from October 26, 1985 to January 24, 1986.

ferences in the frequencies of occurrence cannot be compared between companies due to the difference in sample size, they do indicate that there is a substantial decrease among Lockheed employees when the amount of daily overtime meets or exceeds 12 hours. Therefore, when Lockheed employees worked 12 hours or more, they did so for as many consecutive days as when they worked fewer overtime hours, but they did it less often. While none of the Thiokol employees worked this long for more than seven days in a row, 21.5 percent of the 93 Lockheed employees did so for ten or more consecutive days, some more than once. Furthermore, all of these workers were concentrated in two of the three departments.

There are four individual work histories that illustrate how overextended contract employees became when workload increased at Kennedy. Dave Owen of Lockheed has stated that there are cases of high overtime, but that they occur only occasionally for critically skilled workers in contrast to the general attempt by management to balance the overtime and keep it equally divided among employees.[14]

The first individual is the mechanical technician team leader who was cited earlier for working 60, 96.5, 94, and 80.8 hours per week during the four weeks in January 1986. While this work all began on the first shift at about 8:00 a.m., it often extended until midnight. Across 26 consecutive days he worked only two standard eight-hour days, the remainder consisted of five 16-hour days, 16 12-hour days, and three days of 15, 14, and 13 hours each.

The second employee, an electronic technician, worked the third shift beginning about midnight in another department. From November 5 to 27, he worked 23 consecutive days including 14 that were 11.5 hours long. Then, after two days off, this technician worked 44 days in a row including 29 11.5-hour days, seven 12-hour days, and two 15-hour days.

The third individual is a manager of the technical shops which "are responsible for the fabrication, modification, refurbishment and maintenance of Shuttle ground support systems, equipment and facilities."[15] Starting October 28 he worked 26 consecutive days on the second shift beginning at approximately 4:00 p.m., including 17 days that were 12 or more hours long. In January he continued to work on the same shift for another 26 consecutive days with 18 days each lasting 12 hours or more. Sixteen of these were in succession.

The final worker is a lead electrician responsible for supervising other technicians working on ground support electrical systems and controls. He worked more consecutive days than anyone else in the Lockheed sample. The most disturbing aspect of his work schedule is that all 50 days were on the third shift. This shift usually lasts from midnight to 8:00 a.m., but on 38 of these days he worked 11.5 to 12 hours until about noon.

These four cases are extreme but by no means isolated. They illustrate the frequent pattern at Kennedy of combining weeks of consecutive workdays with multiple strings of 11- or 12-hour days. Research has shown that either of these factors alone produces worker fatigue, but that together they represent a potential threat to safety and worker effectiveness.[16] However, it should be pointed out, as indicated in the report (page 70), the Commission did conclude that the launch site activities, including assembly and preparation, were not a factor in the Challenger accident.

Other studies have demonstrated that night work and shift changes produce sleep loss and fatigue by disrupting workers' Circadian rhythms.[17] Therefore, the additional factor of night shift-

work would enhance the problem for those working for extended long workdays. One group of such workers are the Morton Thiokol employees who typically work 12-hour shifts, either 3:00 p.m. to 3:00 a.m. or 3:00 a.m. to 3:00 p.m., from two to seven days (mean = 4.5 days) in a row while performing the stacking of the Solid Rocket Boosters. Both these extended work schedules disrupt normal sleep patterns by starting or ending at about the usual midpoint of night sleep, thereby producing substantial sleep loss. The occurrence of lengthened workdays of 12 to 16 hours in the preceding four case histories would also disrupt sleep by interrupting the worker's adjustment to his current shift schedule.

This concern is related to the third important aspect of the shiftwork issue, working different shifts. Shiftworkers are known to often require a week or more to adjust to new shifts, especially when the old or new shift is a night shift.[18] Thus, the greatest adjustment difficulty would be in transitioning from the first or second to the third shift or from the third to the second or first shift. A review of all the individual daily records from Lockheed and Thiokol revealed only 26 shift changes among the combined 141 employees in the sample. Thirteen were transitions to or from the third shift. This number of shift changes is relatively few for the length of time under study and suggests that the shift change factor does not warrant serious concern. The only exception to this view is raised by several Lockheed employees who regularly worked the first shift, but who changed to the second or third shift for only a few days several times during the sample period. One of them worked the following schedule: Day 1—8:00 a.m. to 4:00 p.m., Day 2—4:00 p.m. to 2:00 a.m., and Day 3—8:00 a.m. to 10:00 p.m. Such patterns of long hours coupled with abrupt shift changes are likely to increase the potential for shiftwork errors.[19]

In summary, the amount of overtime at Kennedy was often quite high during the time period examined. The 20-hour overtime limit was exceeded 480 times by Morton Thiokol employees and 2,512 times by Lockheed employees, with some individuals experiencing much higher levels than others. The current management policies do not appear to be effective in minimizing this problem. Interviews conducted by the Commission suggest that senior management believes that overtime is being effectively controlled at the working level. When asked what the quality control was to make sure that one or two people weren't working so many hours that they were "burning themselves out and becoming a safety hazard," Dave Owen replied that

> "Normally in a high percentage of cases it's voluntary. The employees volunteer. I think it's management discretion. The supervisor and the manager of the organization have to monitor it. And the people are not bashful; they get tired. . . . You need to realize, if you can, that people are very, for the most part, they are very perceptive of who's working the overtime. They have overtime books, and they themselves try to keep that overtime balanced, because they don't want the guy next to them working all the overtime and they don't get it."[20]

During the same interview both David Owen and Robert Sieck agreed that there is no system at Kennedy for monitoring overtime from the safety perspective.[21] All documentation is oriented toward financial accounting and is not readily amenable to human factors analysis. The development of some type of regular overtime audit procedure combined with more restrictive controls might contribute significantly to reducing the potential safety risks associated with the shiftwork, especially that engendered by unanticipated launch postponements. One such approach has recently been described in a Nuclear Regulatory Commission report which reviews the literature on shiftwork, safety and performance.[22] Much of the overtime revealed in the preceding analysis of workers at Kennedy would be beyond that report's suggested limits for workers at nuclear powerplants, an equally critical industrial setting. It should be recognized, of course, that there is always a trade-off between the desire to keep on duty those personnel with the greatest expertise and the need to guard against the undesirable effects of fatigue. Furthermore, it is not known how much the stimulation and excitement immediately preceding a launch might overcome some of these effects; however, such compensation clearly has its limits.

Overseas Travel

Several of the departments at Kennedy are also required to provide support for contingency landings during Shuttle missions. The assigned individuals travel overseas to alternate landing sites in Africa or Spain. Typically they depart Kennedy several days before a scheduled launch and return soon after completion of the mission. The travel is usually by commercial aircraft across five time zones.

Since most of the travelers are shiftworkers, the issue arises as to whether the added impact of a multiple time zone flight could exacerbate any performance deficit resulting from shiftwork either at Kennedy prior to flight, at the destination or at Kennedy upon return. The proximity of shiftwork to the flight, the shift worked and the direction of flight could all be expected to influence the traveler's ability to perform his job at any given time.[23] Therefore, the daily work hours of the sample of 93 high overtime Lockheed employees were examined to determine whether such travel occurred in conjunction with high overtime or difficult shift schedules. Only travel in support of missions 61-C and 51-L was reviewed.

Of the three departments represented in the sample, only one provided contingency overseas support for those missions. Fourteen individuals performed the necessary travel. Some of these experienced considerable overtime just prior to departing Kennedy. For instance, one worked 107.5 hours the previous ten consecutive days, including six 11.5-hour days and one 12-hour day. He went on duty for the first shift the day after he arrived in Spain. Three other employees who traveled together to Casablanca on January 19, 1986, reported working 96, 79.5, and 79 hours, respectively, for the week ending January 24. Only 16 of those hours were due to travel. Four of the fourteen individuals supported two missions during December and January. One had to return to Dakar only five days after returning from his previous 12-day visit.

This rather limited review of contingency support travel suggests that more attention ought to be paid to the scheduling of such travel in relation to shiftwork and overtime both at Kennedy and overseas. While the likelihood of a contingency landing may be remote, the performance requirements of the ground crew at the alternate site will be critical if the Orbiter experiences the type of emergency that dictates such landings.

Workload and Human Engineering

Any discussion about the safety implications of shiftwork must also address the situational aspects of human error in the workplace. Industry today is well aware that it is important to minimize the potential for such error in the design of industrial equipment and procedures. This requirement becomes even more critical when individuals are required to perform in a high technology environment with the added demands of shiftwork.

Shiftworker fatigue, high workload and faulty equipment design are a combination that can produce unnecessarily high safety risks. The previously described incident during the aborted launch of mission 61-C demonstrates the seriousness of such risks for Shuttle operations. In addition to operator fatigue, the Lockheed incident report on the dumping of 18,000 pounds of liquid oxygen specifically cites several other contributing factors related to the design of the console monitor display, inadequate operator training, poor communications and inadequate staffing.[24] While it may be expedient to address such problems as they occur and solve the problem at hand, the past record suggests that a thorough review of these human factors considerations is needed at Kennedy. The generic issues need to be addressed on a systematic

basis to minimize the future potential for human error in this critical operational environment.

Managers at Risk: The Human Factors of Launch Pressures

The teleconference between Marshall Space Flight Center, Kennedy Space Center and Morton Thiokol, Incorporated, at Wasatch, Utah, focused attention on the advisability of launching mission 51-L and provided a clear opportunity for postponement. The decision should have been based on engineering judgments. However, other factors may have impeded or prevented effective communication and exchange of information.

One factor which may have contributed significantly to the atmosphere of the teleconference at Marshall is the effect on managers of several days of irregular working hours and insufficient sleep.

The extent of sleep loss was documented by Commission investigators who conducted interviews with the teleconference participants at Marshall and Kennedy specifically to reconstruct their daily activities during the five days preceding the accident. As shown in Figure 2, these interviews revealed that because of the launch scrub on January 27 certain key managers obtained only minimal sleep the night before the teleconference or had arisen so early in the morning that they had been awake and on duty for extended periods.[25]

Time pressure, particularly that caused by launch scrubs and rapid turnarounds, increases the potential for sleep loss and judgment errors. This could be minimized by preventing launch support personnel, particularly managers, from combining launch support duty with office work on the same day. The willingness of NASA employees in general to work excessive hours, while admirable, raises serious questions when it jeopardizes job performance, particularly when critical management decisions are at stake.

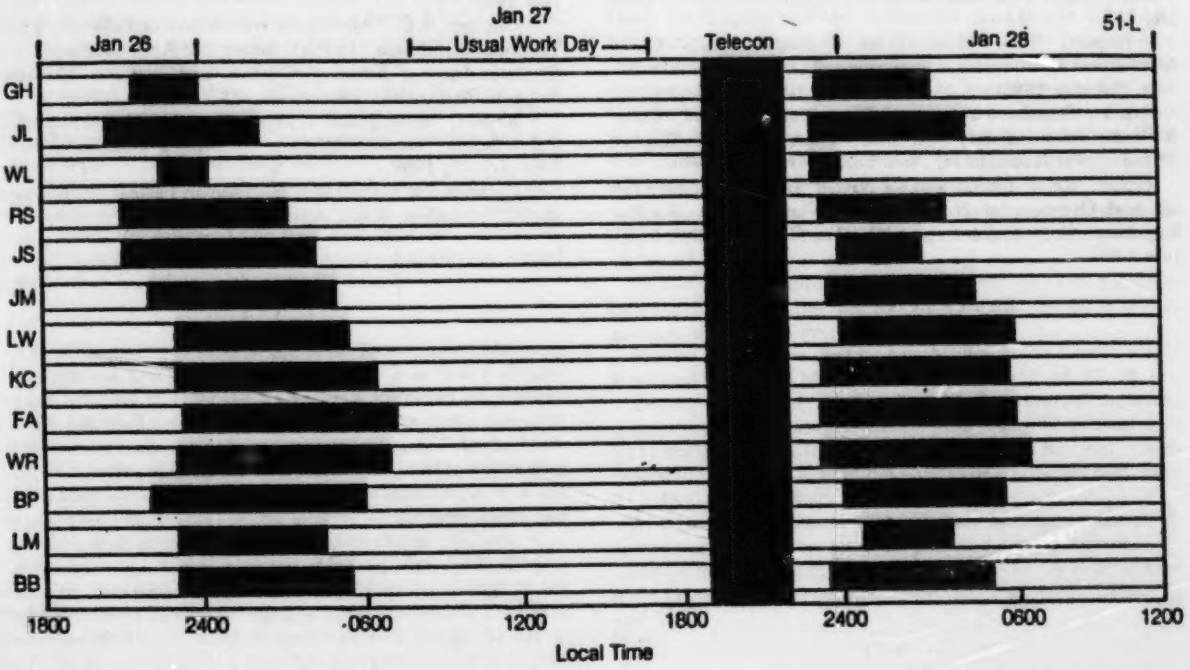

Figure 2—Sleep patterns of Marshall Space Flight Center telecon participants. All times are Central Standard Time except for LM which is Eastern Standard Time.

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Appendix H—Flight Readiness Review Treatment of O-ring Problems

Flight Readiness Review Treatment of O-ring Problems

This Appendix describes case-to-case field joint and nozzle-to-case joint O-ring anomalies experienced in flight and documents to what extent these anomalies were discussed in subsequent Flight Readiness Reviews. The sequence of Flight Readiness Review briefings on the Solid Rocket Boosters included up to five successive briefings at Marshall: SRM Preboard, SRB Board, Shuttle Projects Office Board, and Center Board. The Flight Readiness Review briefings were culminated with a Level I Headquarters briefing, nominally 10 days prior to launch and typically referred to as "the" Flight Readiness Review.

The second Shuttle flight, STS-2, launched November 12, 1981, experienced erosion of the primary O-ring in the right SRM aft field joint. The eroded area was at the 90° location and was a maximum of 0.053 inches deep. However, this erosion was not discussed in the STS-3 Flight Readiness Reviews, even though other anomalies mentioned in these reviews were identified as "Not a Crit. I/II failure." The field joint seal was, of course, classified Criticality 1R. This erosion was the deepest experienced in flight in a case field joint, until STS 51-L.

* * *

STS-6 (flight 6) was the first use of the lightweight SRM case; it was also the first flight following the case joint seal criticality change from 1R to 1. At the STS-6 SRB Preboard on January 4, 1983, Marshall Safety, Reliability, and Quality Assurance mentioned the criticality change as "in approval cycle." At the Marshall Center Board briefing on February 25, 1983, responding to an STS-6 Vehicle Configuration Review action item, Thiokol discussed the gap size and O-ring squeeze for the lightweight case segments, also referring to the criticality change: (Chart 1).

Subsequently, Mr. Lawrence Mulloy, the SRB Project Manager, also mentioned the pending criticality change in his Flight Readiness Review briefing to Level I on March 17, 1983. It was identified as not being an open item, even though the waiver for flight as a Criticality 1 was not approved by Level I until March 28, 1983: (Chart 2).

* * *

STS-6 was launched on April 4, 1983. When the SRMs were dismantled, blowholes through the putty in both nozzle joints were found. The O-rings were affected by heat, but were not eroded. The blowholes were at 318° on the left nozzle and 251° on the right nozzle. These observations were not discussed in any of the STS-7 Flight Readiness Reviews.

* * *

STS 41-B (flight 10), experienced O-ring erosion in both the right hand nozzle joint and the left SRB forward field joint. The field joint O-ring erosion was centered at the 351° location and the area of maximum erosion extended over 3 inches with a maximum depth of 0.040 inches. The nozzle O-ring erosion was at the 14.4° location. The erosion was localized, extending only over a 0.75 inch span to a depth of 0.039 inches. These anomalies were described by Thiokol in the STS 41-C SRB Board briefing on March 2, 1984: (Charts 3, 4).

In the same briefing, O-ring erosion was presented as a technical issue. For the first time in any Flight Readiness Review, the O-ring problems on STS-2 and STS-6 were mentioned. The idea that putty blow holes and O-ring erosion were related was also discussed for the first time: (Charts 5, 6, 7).

On March 8, 1984, at the Shuttle Projects Office Board for STS 41-C (flight 11), the notion of "acceptable" erosion is first mentioned: (Chart 8).

In assessing the erosion, the concern was expressed in terms of the following: erosion of the primary O-ring could lead to erosion of the secondary O-ring and subsequent joint failure. However, the joint had been reclassified as Criticality 1, not 1R, indicating the primary O-ring should have been considered a single point failure. Also noteworthy in this briefing was the first mention of an analysis showing that the "maximum possible" erosion for joint O-rings was .090 inches and the rationale that this was acceptable since a test showed that O-rings with a simulated erosion of .095 inches could seal at three times motor pressure: (Charts 9, 10, 11, 12, 13).

The concept of "acceptable erosion" was advanced again in the Flight Readiness Review briefing to the Marshall Center Board on March 20, 1984: (Chart 14).

At that same briefing, Thiokol discussed the O-ring erosion in some detail. The briefing was substantially the same as that given at the Shuttle Projects Board.

Similar charts were used by Mr. Mulloy at the Level I Flight Readiness Review on March 27, 1984: (Charts 15, 16, 17, 18, 19).

During the Level I briefing, Mr. Mulloy received an action item to review the case and nozzle joint seals. The action item was identified as "Outside the Flight Readiness Review," which indicated that the action did not have to be completed before the STS 41-C flight: (Chart 20).

Mr. Lawrence Wear, the SRM Element Manager, subsequently directed Thiokol to establish a plan and a test program to investigate the issue. In his tasking, he asked Thiokol to determine if the O-ring erosion was acceptable, and if so, why: (Charts 21 and 21A).

* * *

STS 41-C (flight 11), launched April 6, 1984, experienced erosion of the primary O-ring in the right-hand nozzle joint. The erosion, located at 319°, was 0.034 inches deep and extended over a 1.8 inch span. The primary O-ring in the left-hand aft field joint was affected by heat in areas adjacent to blow holes in the putty, but there was no measurable erosion. A Thiokol presentation to the STS 41-D SRM Preboard Flight Readiness Review on May 30, 1984, described these anomalies: (Charts 22, 23, 24, 25, 26).

The nozzle joint O-ring erosion was also discussed as a technical issue in the same briefing: (Charts 27, 28).

Similar charts were prepared by Thiokol for the Marshall Center Board on June 8, 1984, but they were not presented. The STS 41-C O-ring erosion was not mentioned in the STS 41-D Level I Flight Readiness Review on June 18, 1984.

* * *

STS 41-D (flight 12), launched August 30, 1984, experienced primary O-ring erosion in both the right-hand forward field joint and the left-hand nozzle joint. The field joint erosion was 0.028 inches deep and occurred over a 3 inch span at the 275° location. The nozzle O-ring was eroded to a depth of 0.046 inches over a 4 inch span at the 309.6° location. Further, there was a

small amount of soot behind the primary O-ring, indicating short duration blow-by. This was the first occurrence of blow-by in either the case-to-case or nozzle-to-case joints.

At the STS 41-G SRM Preboard on September 12, 1984, Thiokol discussed the 41-D O-ring erosion: (Chart 29).

Mr. Mulloy also discussed the erosion at the 41-G Shuttle Projects Board on September 19, 1984, referring to "allowable" erosion for the first time: (Chart 30).

He used a similar chart at the Marshall Center Board on September 20, 1984: (Chart 31).

The concept of "allowable" erosion was also used at the Level I Flight Readiness Review on September 26, 1984: (Chart 32).

* * *

The next two flights, STS 41-G (flight 13) and STS 51-A (flight 14) experienced no O-ring erosion in either the case-to-case or nozzle-to-case joints. The absence of O-ring damage was noted in the SRM Preboards for STS 51-A and STS 51-C.

* * *

STS 51-C (flight 15), launched January 24, 1985, experienced blow-by in both nozzle joints and erosion and blow-by in two case joints. The calculated O-ring temperature was 53 degrees Fahrenheit, the coldest prior to STS 51-L. The flight hardware evidenced the worst case of "blow-by" experienced by any Shuttle flight. The primary nozzle joint O-rings were not damaged. The primary O-ring in the left-hand forward field joint was eroded 0.010 inches deep over a 4.25 inch span at the 163° location, with a considerable amount of soot between the primary and secondary O-rings. The primary O-ring in the right-hand center field joint was eroded 0.038 inches deep over a 12.5 inch span at the 354° location. There was black grease (sooted) behind the primary O-ring over a 110° arc and the secondary O-ring was affected (but not eroded) by heat over a 29.5 inch span.

At the STS 51-E SRM Preboard on January 31, 1985, Thiokol included a quick-look description of the field joint O-ring damage. The nozzle had not yet been disassembled, so there was no mention of the nozzle joint O-ring blow-by. However, the Thiokol briefing, TWR 14740 Rev B, described the case-to-case field joint O-ring damage in some detail; recounted the pre-flight tang and clevis measurements, putty amounts used, and leak check procedures followed; summarized O-ring damage from previous SRMs; and showed analytical predictions for maximum expected erosion. It concluded with Charts 33 and 34.

The inclusion of the O-ring erosion discussion was apparently the result of the January 31, 1985, "Certified Urgent" message from Mr. Mulloy to Mr. Wear (see Commission Report, Vol. 1, Appendix D).

A much more detailed treatment of the STS 51-C O-ring anomalies was presented to Mr. Mulloy at the SRB Board on February 8, 1985 (some charts were not reproducible and have been retyped): (Charts 35 through 60).

On February 12, 1985, Mr. Mulloy and Thiokol presented a slightly condensed version of the briefing to the Shuttle Projects Office Board. In the Action Items Summary, the 51-C O-ring related items are shown as "closed": (Chart 61).

The Problem Summary portion of the briefing refers to the field joint O-ring blow-by as an "acceptable risk": (Chart 62).

Thiokol then briefed the O-ring erosion as a Special Topic: (Charts 63 through 78).

It should be noted that in this and the preceding briefing, the secondary O-ring was referred to as "a redundant seal using actual hardware dimensions" even though the field joint seal had been officially classified as Criticality 1 (not redundant) for two years. Also, both briefings as part of their conclusion on O-ring erosion offered that "low temperature enhanced probability—STS 51-C experienced worst case temperature change in Florida history."

At the February 14, 1985 Marshall Center Board, Mr. Mulloy did not address the 51-C O-ring anomalies in detail: (Chart 79).

At the Level I Flight Readiness Review on February 21, 1985, Mr. Mulloy again did not present a detailed briefing, presenting only two charts: (Charts 80 and 81).

After the Commission Report was published, the Commission received a videotape of Mr. Mulloy presenting the STS 51-E Level I Flight Readiness Review. The transcript of the portion pertaining to the preceding two charts is included with the charts.

The mission designated STS 51-E never flew. Payload problems forced a change in the cargo manifesting and STS 51-D (flight 16) was the next launch. The Shuttle hardware scheduled for STS 51-E was actually used on STS 51-B (flight 17) after STS 51-D. The STS 51-D Flight Readiness Reviews did not readdress STS 51-C performance; only those issues associated with the processing of the STS 51-D elements were discussed.

* * *

STS 51-D (flight 16), launched April 12, 1985, experienced erosion of the primary O-rings in both nozzle joints. The right-hand nozzle primary O-ring eroded to a depth of 0.068 inches over a 6 inch span at 116°. The left-hand nozzle primary O-ring eroded to a depth of 0.011 inches over a 2.12 inch span at the 14.4° position. There was no blow-by past either nozzle O-ring.

The Board for STS 51-B (flight 17) was conducted on April 8, 1985, before the STS 51-D launch. Consequently, STS 51-D anomalies were not discussed; however, the nozzle from STS 51-C (flight 15), had been disassembled by this time and the O-ring blow-by discovered. The findings were presented to Mr. Mulloy: (Charts 82, 83, 84).

There was no mention of either the STS 51-C or STS 51-D nozzle anomalies at the STS 51-B Shuttle Projects Board on April 17, 1985, or the Level I Flight Readiness Review on April 23, 1985.

* * *

STS 51-B (flight 17), launched April 29, 1985, suffered the worst O-ring erosion experienced prior to STS 51-L. The left-hand nozzle primary O-ring eroded to a depth of 0.171 inches over a 1.59 inch span at the 54° location. There was evidence of considerable blow-by. The secondary O-ring was eroded to a depth of 0.032 inches over a 3.1 inch span, also at the 54° location. The right-hand nozzle O-ring eroded to a depth of 0.005 inches over a 3.4 inch span at the 14.4° location. There was no blow-by associated with this erosion.

The SRB Board for STS 51-F (flight 19) and STS 51-G (flight 18) were combined and held on May 8, 1985, before the STS 51-B (flight 17) nozzles had been disassembled. It was noted that there were blow holes through the putty in one field joint from each of the STS 51-B SRMs; however, the O-rings were not damaged. No O-ring related anomalies were discussed at the STS 51-G Shuttle Projects Board on May 29, 1985, the Center Board on May 31, 1985, or the Level I Flight Readiness Review on June 11, 1985.

* * *

STS 51-G (flight 18), launched June 17, 1985, experienced blow-by and erosion in both nozzle joints. The right-hand nozzle primary O-ring was eroded in two different places—0.023 inches over a 0.88 inch span at 342° and 0.009 inches over a 2 inch span at 270°. The left-hand nozzle primary O-ring eroded to a depth of 0.013 inches over a 1.12 inch span at 151.2°. There was blow-by associated with all three locations, although neither of the secondary O-rings were damaged.

The Flight Readiness Review process for STS 51-F (flight 19) continued with an update SRB Board on June 21, 1985. The Shuttle Projects Board occurred on June 25, 1985. At this time, the STS 51-B (flight 17) nozzle joint O-ring damage had still not

yet been discovered, nor had the STS 51-G nozzle been disassembled. Before the STS 51-F Marshall Center Board Flight Readiness Review on June 27, 1985, took place, the STS 51-B nozzle O-ring anomaly was finally discovered. Mr. Mulloy addressed the issue at the Center Board: (Charts 85 through 95).

On July 1, 1985, Thiokol presented a more extensive analysis of the STS 51-B anomaly at a combined Flight Readiness Review for the Marshall SRM Preboard, SRB Board, Shuttle Projects Office Board, and Marshall Center Board: (Charts 96 through 129).

Mr. Mulloy's briefing to the Level I Flight Readiness Review the next day (July 2, 1985) presented the 51-B O-ring erosion problem as "closed," offering a resolution based on the use of a higher (200 psi) leak check stabilization pressure and introducing for the first time a rationale for accepting secondary O-ring erosion: (Charts 130, 131, 132, 133).

The Commission could find no reference to the STS 51-D (flight 16) and STS 51-G (flight 18) nozzle joint O-ring anomalies in any Flight Readiness Review.

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STS 51-F (flight 19) was launched on July 29, 1985, and experienced no O-ring erosion; however, there was a blow hole through the putty in the right-hand SRM nozzle and the primary O-ring was affected by heat.

The SRM nozzles were apparently being disassembled much faster than previously; the absence of STS 51-F nozzle O-ring damage was noted at STS 51-I Shuttle Projects Board on August 7, 1985, the Marshall Center Board on August 13, 1985, and the Level I Flight Readiness Review on August 15, 1985.

• • •

On August 19, 1985, Thiokol presented to Level I a detailed discussion and analysis of primary seal erosion in the igniter, field, and nozzle joints. The briefing, prepaid at the request of Level I, was prompted by heightened concern following the STS 51-B (flight 17) nozzle joint anomaly. Although not an element of the Flight Readiness Review process, the briefing is included here because of its inherent importance and because it was the vehicle through which Marshall attempted to close the April 5, 1984, Action Item from the STS 41-C Level I Flight Readiness Review: (Charts 134 through 188).

After the briefing, Mr. Mulloy submitted a request to close the STS 41-C Action Item: (Chart 189).

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STS 51-I (flight 20), launched August 27, 1985, suffered primary O-ring erosion in two locations on the left-hand SRM nozzle joint: 0.064 inches deep over a 13.5 inch span at the 18° location and 0.030 inches deep over a 1.5 inch span at the 0° location. There was no blow-by associated with either occurrence.

Mr. Wear briefed the O-ring damage at the STS 51-J SRB Board Flight Readiness Review on September 9, 1985: (Chart 190).

At the STS 51-I Shuttle Projects Board on September 17, 1985, the Center Board on September 19, 1985, and the Level I Flight Readiness Review on September 26, 1985, the incident was simply itemized as "LH nozzle to case primary O-ring erosion within experience base."

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STS 51-J (flight 21) flew on October 3, 1985, and experienced no O-ring damage. Anomalies were briefed as "TBD" at the STS 61-A SRB Board Flight Readiness Review on October 7, 1985, possibly indicating that the SRMs had not been inspected. At the Shuttle Projects Board on October 15, 1985, the lack of O-ring erosion was noted: "SRM joint O-ring performance nominal."

STS 61-A (flight 22) launched October 30, 1985, experienced erosion of the right-hand nozzle primary O-ring to a depth of 0.075 inches over a 13 inch span at the 97.2° location. Also experienced on STS 61-A was the first case-to-case field joint O-ring anomaly since mission STS 51-C. There was blow-by past the primary O-rings in the center and aft field joints on the left-hand SRM. The O-rings were not damaged.

The anomalies were not discussed at the STS 61-B SRB Board on November 4, 1985; however, at the Shuttle Projects Board on November 6, 1985, Mr. Mulloy's briefing included the note: "SRM joint O-ring performance within experience base." At the Marshall Center Board on November 12, 1985, and the Level I Flight Readiness Review on November 18, 1985, he briefed that "Post flight inspection of SRM revealed hot gas erosion of primary nozzle/case joint-O-ring on RH SRM—Within previously accepted experience."

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STS 61-B (flight 23), launched November 26, 1985, experienced primary O-ring erosion in both nozzle joints. The right-hand nozzle O-ring eroded 0.039 inches over a 7 inch span at the 0° position. The left-hand nozzle O-ring eroded 0.017 inches over a 3 inch span at the 345.6° location. There was blow-by past the primary O-ring in the left-hand nozzle joint.

These observations were briefed at the STS 61-C SRB Board Flight Readiness Review on December 2, 1985: (Chart 191).

At the December 4, 1985 STS 61-C Shuttle Projects Board, Mr. Mulloy noted "SRM joint O-ring performance within experience base." The Commission's copy of the December 9, 1985 Marshall Center Board briefing was incomplete; however, at the December 11, 1985 Level I Flight Readiness Review, it was reported that there were "No 61-B flight anomalies."

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STS 61-C (flight 24), launched on January 12, 1986, experienced nozzle joint O-ring erosion and blow-by and field joint O-ring erosion. The right-hand nozzle joint primary O-ring was eroded 0.011 inches over an 8 inch span at the 162° location. There was blow-by past the primary O-ring in the left-hand nozzle joint between the 255.6° and 334.8° positions. The primary O-ring in the left SRM aft field joint was eroded 0.004 inches over a 3.5 inch span at the 154° location.

The STS 51-L SRB Board Flight Readiness Review on January 3, 1986, Shuttle Projects Board on January 8, 1986, and Marshall Center Board on January 13, 1986, all occurred before the STS 61-C SRBs were available for inspection. However, at the STS 51-L Level I Flight Readiness Review on January 15, 1986, Mr. Mulloy noted that there were "No 61-C Flight Anomalies," and that there were "No Major Problems or Issues."

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STS 51-L (flight 25) was launched on January 28, 1986.

STS-6 FLIGHT READINESS REVIEWS: Charts 1-2

Chart 1

Marshall Center Board (February 25, 1983)

ACTION	RESPONSE
SRB-4 DEVELOP RATIONALE FOR ACCEPTANCE OF SECONDARY SEAL CONDITION FOR STANDARD WEIGHT AND LIGHTWEIGHT CASES AND PROVIDE RECOMMENDATIONS CONCERNING SHIMMING	• JOINT SEAL INTEGRITY CONTROLLED BY: TANG/CLEVIS DIMENSIONS O-RING GROOVE WIDTH AND DEPTH O-RING DIAMETER JOINT ASSEMBLY PROCEDURES SHIM INSTALLATION • SRM JOINT PRIMARY O-RING SEAL IS VERIFIABLE AFTER ASSEMBLY BY LEAK TEST • STS-6 HAS MINIMUM INITIAL O-RING SQUEEZE OF 15.1 PERCENT AND A MAXIMUM GAP OF 0.015 IN. • LABORATORY TESTS HAVE SUCCESSFULLY SEALED 1,600 PSI WITH 5 PERCENT INITIAL O-RING SQUEEZE AND 0.125 IN. GAP • TITAN 120 IN. DIAMETER SRM HAS 1,076 SUCCESSFUL MOTOR JOINT TESTS WITH SIMILAR, BUT SIMPLEX NONVERIFIABLE SEAL CONFIGURATION • EIGHTEEN SRM FIRINGS (54 FIELD JOINTS) SUCCESSFULLY DEMONSTRATE PRIMARY O-RING SEAL INTEGRITY • CURRENT SHIM CONFIGURATION PROVIDES ADEQUATE O-RING SQUEEZE • SECONDARY SEAL CONDITION AND RATIONALE APPROVED BY SPACE SHUTTLE CRITICAL ITEM LIST (CIL) • RATIONALE REVIEWED AND ACCEPTED BY STS-6 FRR PREBOARD

Thiokol/WASATCH DIVISION

Chart 2

Level I (March 17, 1983)

ORGANIZATION: SHUTTLE PROJECTS OFFICE SOLID ROCKET BOOSTER	MARSHALL SPACE FLIGHT CENTER SRB STS-6 FLIGHT READINESS REVIEW	NAME: L. MULLOY
CHART NO.:		DATE: MARCH 17, 1983

CERTIFICATION OF FLIGHT READINESS REVIEW (COFR) EXCEPTIONS

CATEGORY	OPEN ITEMS	REMARKS
1. OPEN NON CONFORMANCES	NONE	
2. CERTIFICATE OF QUALIFICATION	NONE	SIXTEEN (16) COQ'S HAVE BEEN UPDATED AND APPROVED SINCE STS-6
3. CORRECTIVE ACTION PROBLEM SUMMARY	NONE	
4. HAZARDS	NONE	ONE NEW HAZARD IDENTIFIED SINCE STS-5. (CLOSED)
5. DEVIATION APPROVAL REQUESTS	NONE	NONE
6. FMEA/CIL CHANGES	NONE	FMEA ACCOMPLISHED ON INTEGRATED RECEIVER/DECODER AND RF DOWN LINK SYSTEM – NO ADDITIONAL FAILURE MODES IDENTIFIED. CASE "B" RING LEAKAGE CHANGED TO CRITICALITY 1 – WAS 1R.

Chart 3

SRB Board (March 2, 1984)

STS-11 Postflight Inspection (Cont)

Motor/Component	Condition	Comments
Left forward center segment	Numerous spotty patches of Rust-Oleum® paint and primer missing along forward case segment. Typically in axial strings between axial Stations 900 and 1000. (Size: 1 to 2 in. axial by 0.5 to 0.7 in. circumferential) Most heavily concentrated between 340 and 0 deg, but exist around full case circumference. No excessive heating or discoloration evident.	Falls between STS-5L aft segment and STS-9L aft center segment experience
Left forward center segment field joint (Station 851.5)	An internal gas path through the zinc chromate putty to the primary O-ring occurred. The O-ring contained a flat eroded section 3 in. long where approximately 0.045 of the O-ring dia was heat affected	O-ring erosion was previously experienced once on STS-2R aft segment (see technical issues)

Chart 4

STS-11 Postflight Inspection (Cont)

Motor/Component	Condition	Comments
Right-hand nozzle	An internal gas path through the zinc chromate putty to the primary O-ring occurred. The O-ring contained a flat eroded section 0.75-in. long where approximately 0.050 of the O-ring dia was heat affected	O-ring erosion was previously experienced once on STS-2R aft segment (see technical issues)

Chart 5

STS-11 O-ring Anomalies

- Findings
  - Hot gas path through putty
  - Primary O-ring erosion
  - No leakage past primary O-ring

	Cross-Sectional View			Top View	
	Erosion Depth (in.)	Perimeter Affected (deg)	Nominal Diameter (in.)	Length of Maximum Erosion (in.)	Total Heat Affected Length (in.)
STS-11A forward field	0.040	217	0.280	3.0	14.5
STS-11B nozzle	0.039	103.5	0.275	0.75	45
STS-6A nozzle*	None	None	0.275	None	None
STS-6B nozzle*	None	None	0.275	None	None
QM-4 nozzle	0.051	101	0.275	5	11
STS-2 aft field	0.053	116	0.280	--	--

*Gas path through putty, but no O-ring damage

Chart 6

STS-11 O-ring Anomalies (Cont)

- Probable causes
  - Putty blow-through at ignition causes cavity between putty and primary O-ring to fill during pressurization
    - Inability of putty to withstand motor pressure
    - Air entrapment in putty during mating
    - Blow holes in putty during joint leak test

Chart 7

STS-11 O-ring Anomalies (Cont)

- Engineering analysis
  - Dimensional stackup shows adequate O-ring squeeze to effect seal for both primary and secondary O-rings
    - Thermal analysis shows maximum expected erosion to be approximately what has been experienced
- Concerns
  - If primary O-ring allowed a hot gas jet to pass through, would the secondary O-ring survive the impingement?

Chart 8

Shuttle Projects Office Board (March 8, 1984)

PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION FOR STS-13	TO BE DISCUSSED
• NON UNIFORM NOZZLE EROSION (POCKETS)	• MISSION PERFORMANCE/ SAFETY	• FACTOR OF SAFETY ACCEPTABLE	• YES
• O-RINGS AT STS-11A FORWARD - FORWARD CENTER SEGMENT FIELD JOINT AND STS-11B NOZZLE TO AFT SEGMENT JOINT ERODED	• MISSION PERFORMANCE/ SAFETY	• EROSION IS ACCEPTABLE MOST PROBABLE CAUSE IDENTIFIED	• YES
• OUT-OF-ROUND CLEVIS JOINT	• REUSE/MAINTENANCE	• STRUCTURALLY & FUNC-TIONALLY ACCEPTABLE FOR STS-13	• NO
• LOT 0006 VACUUM PUTTY DR AT WASATCH (PUTTY RECONDITIONED)	• MISSION PERFORMANCE/ SAFETY	• RECONDITIONED PUTTY NOT ON STS-13 LABORATORY TESTS ' RECONDITIONED PU' ACCEPTABLE	• NO
• NOZZLE CARBON PHENO-LIC HAS MINOR DELA-MINATIONS	• MISSION PERFORMANCE/ SAFETY	• MRB VERIFIES DELAMINA-TIONS WITHIN EXPERIENCE BASE	• NO

SRM 6

Chart 9

STS-11 (SRM-10) O-ring Erosion Assessment

- **Problem**
  - **Forward center-to-forward field joint and nozzle-to-fixed housing primary O-rings eroded**
- **Concern**
  - **Erosion through primary O-ring could cause hot gas impingement on secondary O-ring**
  - **Erosion of secondary O-ring could cause joint seal failure**
  - **Joint seal failure is criticality 1**
- **Discussion**
  - **Similar O-ring erosion observed on STS-2 aft field joint, QM-4 nozzle (STS-6A and STS-6B showed evidence of heating but not erosion)**
  - **Postflight inspection of O-ring erosion indicates short time, localized impingement of hot gas**
  - **Postflight inspection of joints shows gas path through putty**

SRM-35

Chart 10

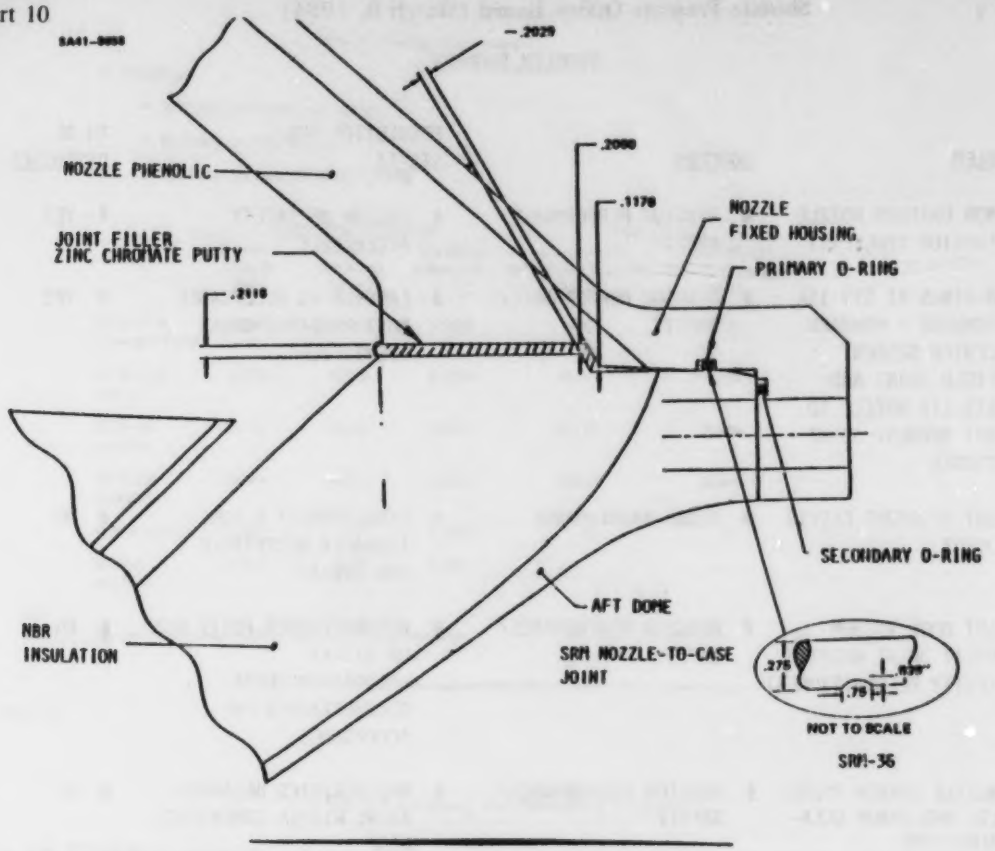


Chart 11

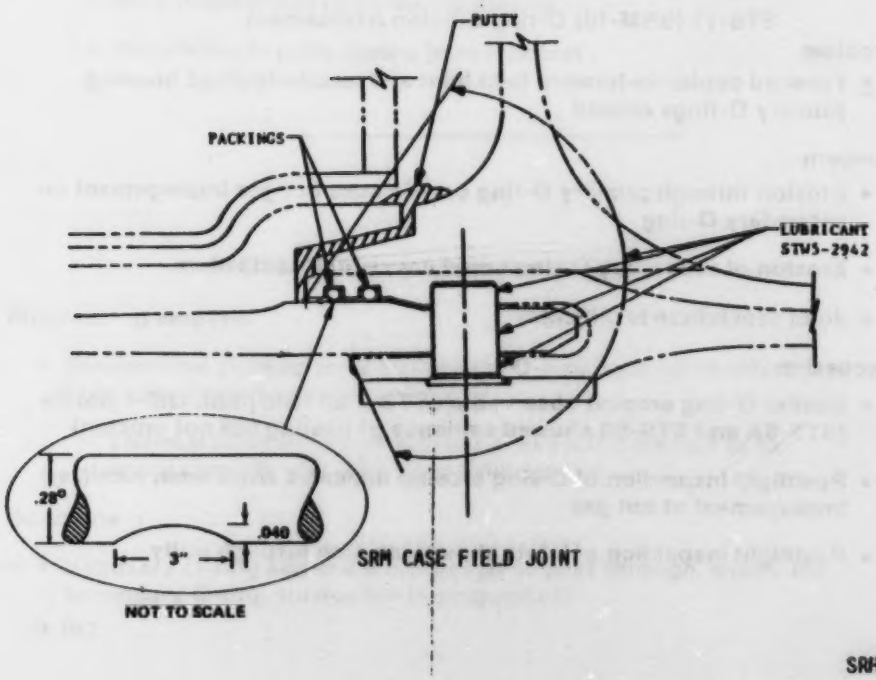


Chart 12

STS-11 (SRM-10) O-RING EROSION ASSESSMENT

- MOST PROBABLE MECHANISMS FOR CREATING GAS PATHS ARE:
  - 1 VOID EXISTS IN PUTTY DUE TO AIR ENTRAPMENT DURING JOINT ASSEMBLY

    -OR-
  - 2 BLOW THROUGH DURING INITIAL LEAK CHECK PRESSURIZATION

    -OR-
  - 3 LACK OF PUTTY LOCALLY DUE TO JOINT ECCENTRICITY
- RATIONALE FOR ACCEPTING POSSIBILITY OF JOINT O-RING EROSION ON STS-13
  - CONSERVATIVE ANALYSIS INDICATES MAX EROSION POSSIBLE

    0.090 IN. (FIELD JOINT)

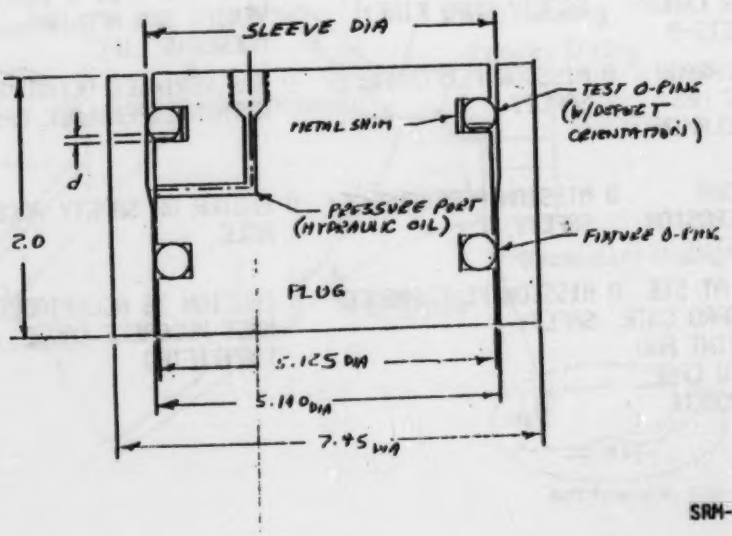
    ~0.090 (NOZZLE)
  - LABORATORY TEST OF FULL-SCALE O-RING/JOINT CROSS SECTION SHOWS CAPABILITY TO SUSTAIN JOINT SEALING INTEGRITY AT 3,000 PSI PRESSURE, USING AN O-RING WITH A SIMULATED 0.095 IN. EROSION DEPTH
- RECOMMENDATION
  - FLY STS-13, ACCEPTING POSSIBILITY OF SOME O-RING EROSION DUE TO HOT GAS IMPINGEMENT

SRM-38

Chart 13

STS-11 O-RING ANOMALIES

O-RING DIMENSIONAL ANALYSIS



SRM-39

Chart 14

Marshall Center Board (March 20, 1984)

PROBLEM SUMMARY (CONT'D)

PROBLEM	CONCERN	RESOLUTION FOR STS-13	TO BE DISCUSSED
• NON UNIFORM NOZZLE EROSION (POCKETS)	• MISSION PERFORMANCE/ SAFETY	• FACTOR OF SAFETY ACCEPTABLE	YES
• O-RINGS AT STS-11B FORWARD CENTER FIELD JOINT AND NOZZLE TO CASE JOINT ERODED	• MISSION PERFORMANCE/ SAFETY	• EROSION IS ACCEPTABLE MOST PROBABLE CAUSE IDENTIFIED	YES
• OUT-OF-ROUND CLEVIS JOINT	• REUSE/MAINTENANCE	• STRUCTURALLY & FUNCTIONALLY ACCEPTABLE FOR STS-13	NO
• LOT 0006 VACUUM PUTTY DR AT WASATCH (PUTTY RECONDITIONED)	• MISSION PERFORMANCE/ SAFETY	• LABORATORY TESTS VERIFY RECONDITIONED PUTTY ACCEPTABLE	NO
• NOZZLE CARBON PHENOLIC HAS MINOR DELAMINATIONS	• MISSION PERFORMANCE/ SAFETY	• MRB VERIFIES DELAMINATIONS WITHIN EXPERIENCE BASE	NO
• ONE MAIN PARACHUTE FAILED TO INFLATE ON EACH SRB (STS-11)	• REUSE/MAINTENANCE	• ALL MAIN PARACHUTES UNPACKED AND REPACKED TO IMPROVED PROCEDURE (LS03-4 PCN-9)	NO
• STS-13 SRB PARACHUTE SYSTEM REQUIREMENTS ENVELOPE (REENTRY TRAJECTORY END-CONDITIONS)	• REUSE/MAINTENANCE	• ACCEPT 6% PROBABILITY OF ENVIRONMENTAL EXCEEDANCE	NO

Level I (March 27, 1984)

Chart 15

MSFC SHUTTLE PROJECTS | SOLID ROCKET BOOSTER | L. MULLOY MARCH 27, 1984 PAGE 7

PROBLEM SUMMARY

PROBLEM	CONCERN	FOR STS 41-C	DISCUSSED
O ORBITER APU INJECTOR CRACKING ON STS-9	O MISSION PERFORMANCE/ SAFETY (HPU FIRE)	O ANALYSIS TEST & INSPECTION VERIFY SRB HPU HAS ADEQUATE LIFE	NO
O NOZZLE CARBON PHENOLIC HAS MINOR DELAMINATIONS	O MISSION PERFORMANCE/ SAFETY	O MRB VERIFIES DELAMINATIONS WITHIN EXPERIENCE BASE	NO
O NONUNIFORM NOZZLE EROSION (POCKETS)	O MISSION PERFORMANCE/ SAFETY	O FACTOR OF SAFETY ACCEPTABLE	YES
O O-RINGS AT STS 11B FORWARD CNTR FIELD JOINT AND NOZZLE TO CASE JOINT ERODED	O MISSION PERFORMANCE/ SAFETY	O EROSION IS ACCEPTABLE MOST PROBABLE CAUSE IDENTIFIED	YES

SRB-10

Chart 16

MSFC SHUTTLE PROJECTS	SOLID ROCKET BOOSTER	L. MULLOY MARCH 27, 1984 PAGE 36

STS 41-B (SRM-10) O-RING EROSION ASSESSMENT

- PROBLEM
  - FORWARD CENTER-TO-FORWARD FIELD JOINT AND NOZZLE-TO-FIXED HOUSING PRIMARY O-RINGS ERODED
- CONCERN
  - EROSION THROUGH PRIMARY O-RING COULD CAUSE HOT GAS IMPINGEMENT ON SECONDARY O-RING
  - EROSION OF SECONDARY O-RING COULD CAUSE JOINT SEAL FAILURE
  - JOINT SEAL FAILURE IS CRITICALITY 1
- DISCUSSION
  - SIMILAR O-RING EROSION OBSERVED ON STS-2 AFT FIELD JOINT, QM-4 NOZZLE (STS-6A AND STS-6B SHOWED EVIDENCE OF HEATING BUT NOT EROSION)
  - POSTFLIGHT INSPECTION OF O-RING EROSION INDICATES SHORT TIME, LOCALIZED IMPINGEMENT OF HOT GAS
  - POSTFLIGHT INSPECTION OF JOINTS SHOWS GAS PATH THROUGH PUTTY

Chart 17

SRM NOZZLE-TO-CASE JOINT

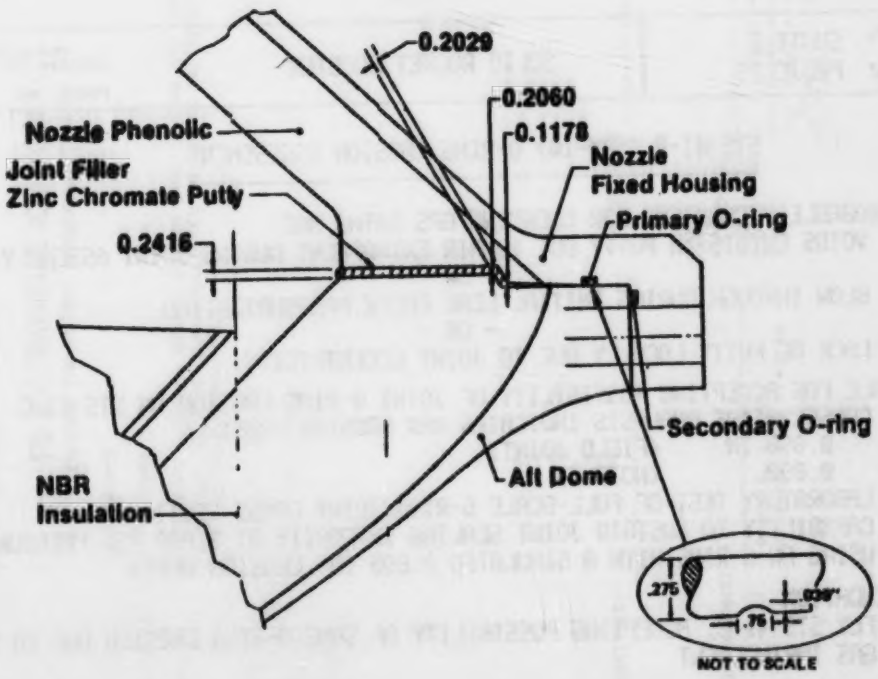


Chart 18

SRM CASE FIELD JOINT

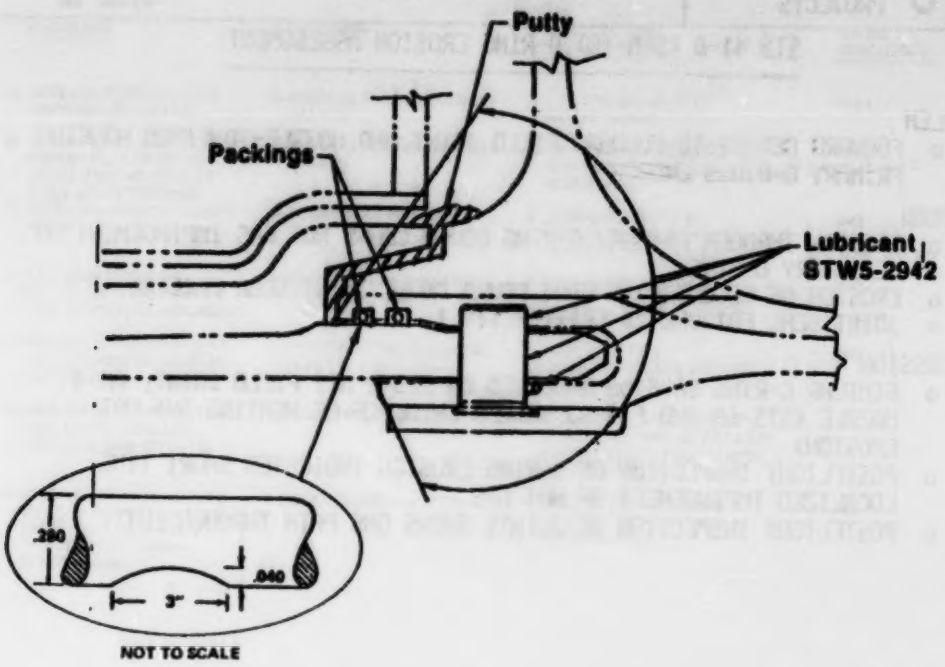


Chart 19

MSFC SHUTTLE PROJECTS	SOLID ROCKET BOOSTER	L. MULLOY MARCH 27, 1984 PAGE 39

STS 41-B (SRM-10) O-RING EROSION ASSESSMENT

- MOST PROBABLE MECHANISMS FOR CREATING GAS PATHS ARE:
  - VOIDS EXISTS IN PUTTY DUE TO AIR ENTRAPMENT DURING JOINT ASSEMBLY
    - OR -
  - BLOW THROUGH DURING INITIAL LEAK CHECK PRESSURIZATION
    - OR -
  - LACK OF PUTTY LOCALLY DUE TO JOINT ECCENTRICITY
- RATIONALE FOR ACCEPTING POSSIBILITY OF JOINT O-RING EROSION ON STS 41-C
  - CONSERVATIVE ANALYSIS INDICATES MAX EROSION POSSIBLE
    - 0.090 IN. (FIELD JOINT)
    - 0.090 (NOZZLE)
  - LABORATORY TEST OF FULL-SCALE O-RING/JOINT CROSS SECTION SHOWS CAPABILITY TO SUSTAIN JOINT SEALING INTEGRITY AT 3,000 PSI PRESSURE USING AN O-RING WITH A SIMULATED 0.095 IN. EROSION DEPTH
- RECOMMENDATION
  - FLY STS 41-C, ACCEPTING POSSIBILITY OF SOME O-RING EROSION DUE TO HOT GAS IMPINGEMENT

Chart 20

FEB 7 '86 15:26 ROOM2157 PAGE.01

STS 41-C PROGRAMMATIC ACTION ITEM

(OUTSIDE THE FLIGHT READINESS REVIEW)

'ER: 3-36-4-2

INITIATOR: DR. MARK

ACTION: PERFORM A FORMAL REVIEW OF SRM CASE-TO-CASE AND CASE-TO-NOZZLE JOINT SEALING PROCEDURES TO ENSURE SATISFACTORY CONSISTENT CLOSEOUTS.

ACTIONEE: MSFC/L. MULLOY

DUE DATE: MAY 30, 1984

CLOSEOUT:

SUBMITTED: _____

CONCURRENCE: _____

CONCURRENCE: _____
Glynn S. Lunney
Manager, NSTS Program

APPROVED: _____
J. A. Abrahamson
Associate Administrator
for Space Flight
LMW 5 Apr 84

Chart 21

FEB 19 '86 15:15 AL-827/MSFC 4202 345A PAGE.34

National Aeronautics and Space Administration

George C. Marshall Space Flight Center
George C. Marshall Space Flight Center, Alabama
35812

APR 11 1984

In Reply Refer To: SA42-174-84

Morton-Thiokol, Inc., Wasatch Division
Attn: Mr. Joe Kilminster
Vice President, Space Booster Programs
P.O. Box 524
Brigham City, UT 84302

Subject: Review of SRM Case-to-Case and Case-to-Nozzle Joint Sealing Procedures

41-C for M-11

Based on the STS-11 o-ring anomaly and the o-ring anomalies experienced on QM-4, STS-2, and STS-6A and 6B, MTI has initiated a study to evaluate the o-ring erosion in the case and nozzle joints. During the STS-13 FRR with Level I, the following action was assigned to the SRM Office, "Perform a formal review of SRM case-to-case and case-to-nozzle sealing procedures to assure satisfactory and consistent closeouts".

MTI, in conjunction with the already ongoing effort, is requested to establish a plan and a test program to formally respond to the above action. Based on discussions between Messrs Ron McIntosh, Keith Coates, Bob Eblirg and Brian Russell, the MTI response should address, but not be limited to, the following areas:

1. ANALYSIS

   - Identify cause of o-ring erosion
   - Is the o-ring erosion acceptable, if so - why?
   - Define specific changes required to prevent o-ring erosion.
   - Define for the putty the effects of:
     Variations of material characteristics
     Layup configuration
     As received condition versus environmental exposure
     Manufacturing sources/qualification procedures

2. TEST

   - Small motor tests to simulate effects on volume variations, flow patterns, exposed o-ring area, etc.
   - SRM Motor segment joint tests to evaluate pressures and putty geometry changes during assembly
   - Investigate optimum putty location in both case and nozzle joints with subscale tests

3 INSPECTION TEAM

- Establish a group of experienced people to witness and critique joint assemblies at the plant and disassemblies at KSC and Clearfield for each SRM.
- MSFC will participate in the MTI group reviews

4. SCHEDULE

- Provide schedule for the plan

MTI is requested to provide a formal response to the Level I action by May 15, 1984. In addition the MTI response should address the igniter adapter-to-case joint where applicable.

L. O. Wear
Manager, SRM Office

cc:
SA41/Messrs. Mulloy/Caruso
SA42/Messrs Thomas/McIntosh
SA49/Mr. Burks
ZE11/Messrs Horton/Coates
MTI-WAS/Messrs McDonald/Ebling/Russell
MTI-HSV/Mr. Parker

STS 41-D FLIGHT READINESS REVIEWS: Charts 22-28

SRM Preboard (May 30, 1984)

Chart 22

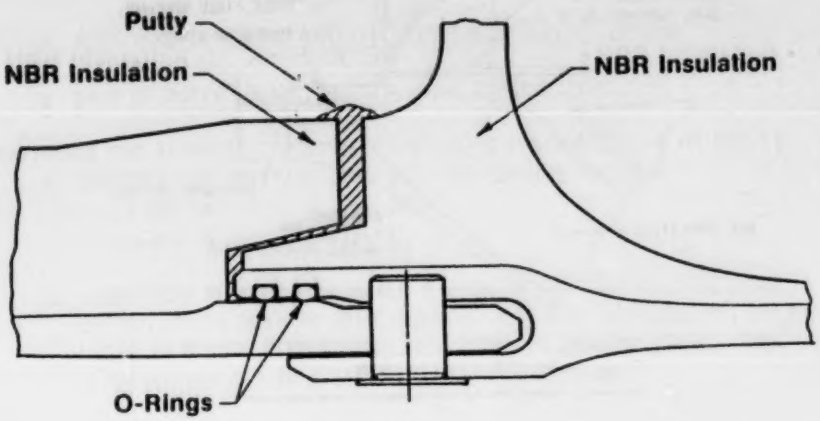
PROBLEM SUMMARY (CONT)
41-C (STS-13) POSTFLIGHT HARDWARE ASSESSMENT (CONT)

- O STS-13 JOINT INSPECTION
  - O BOTH LEFT (A61) AND RIGHT (A62) CASE FIELD JOINTS
    - O NO HEAT DAMAGE TO ANY O-RING
  - O A61 FIELD JOINTS
    - O PUTTY WAS SEPARATED FROM INSULATION AND CHARRED OVER A 90° ARC FROM 330° TO 60° ON FORWARD FACING INHIBITOR SURFACE ON AFT JOINT
    - O INTERMITTENT CORROSION ON INNER LEG OF STEEL CLEVIS BELOW PUTTY SEPARATION
  - O A62 FIELD JOINTS
    - O NO CORROSION - GOOD GREASE COVERAGE
    - O CHARRED POCKET IN PUTTY AT 214° IN FWD CENTER TO AFT CENTER JOINT

Chart 23

PROBLEM SUMMARY (CONT)
41-C (STS-13) POSTFLIGHT HARDWARE ASSESSMENT (CONT)

SRM CASE FIELD JOINT



SRM-HPM Field Joint

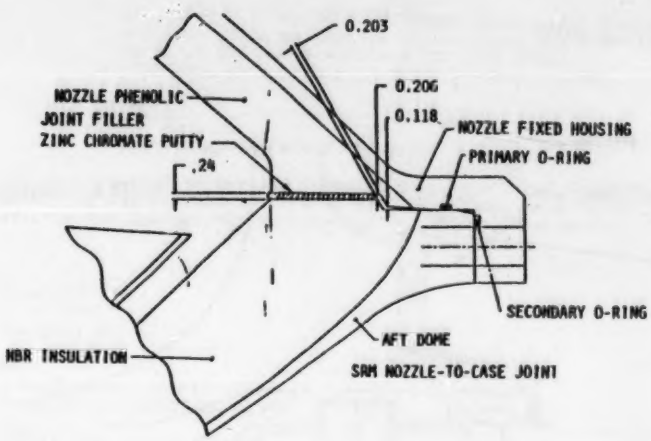
Chart 24

PROBLEM SUMMARY (CONT)
41-C (STS-13) POSTFLIGHT INSPECTION (CONT)

- STS-13 JOINT INSPECTION (CONT)
  - NOZZLE JOINTS
    - STS-13A - COMPLETE PUTTY COVERAGE ON NOZZLE, NO HOT GAS PATHS
    - STS-13B
      - GAS PATHS THROUGH PUTTY AT 319, 338 AND 347 DEGREES
      - DAMAGED O-RING AT 319 DEGREES
        - MAXIMUM CROSS-SECTIONAL DEPTH - .034 INCH
        - O-RING CROSS-SECTIONAL PERIMETER AFFECTED - 136 DEGREES
        - TOTAL HEAT AFFECTED O-RING CIRCUMFERENTIAL LENGTH - 5.56 INCHES
      - NO DAMAGE AT OTHER GAS PATH LOCATIONS

Chart 25

PROBLEM SUMMA. (CONT)
41-C (STS-13) POSTFLIGHT HARDWARE ASSESSMENT (CONT)



SRM NOZZLE TO CASE JOINT

Chart 26

PROBLEM SUMMARY (CONT)
41-C (STS-13) POSTFLIGHT HARDWARE ASSESSMENT (CONT)

- CONCLUSIONS
  - ALL PRIMARY SEALS PERFORMED WELL
    - NO COMPROMISE TO STS-13 PERFORMANCE
    - SIMILAR O-RING EROSION SEEN ON PREVIOUS MOTORS, I.E. QM-4, STS-2, AND STS-11

Chart 27

TECHNICAL ISSUES
STS-13 O-RING/VACUUM PUTTY ANALYSIS (CONT)

- PROBLEM
  - NOZZLE-TO-FIXED HOUSING PRIMARY O-RINGS ERODED
- CONCERN
  - EROSION THROUGH PRIMARY O-RING COULD CAUSE HOT GAS IMPINGEMENT ON SECONDARY O-RING
  - EROSION OF SECONDARY O-RING COULD CAUSE JOINT SEAL FAILURE
  - JOINT SEAL FAILURE IS CRITICALITY 1
- DISCUSSION
  - SIMILAR O-RING EROSION OBSERVED ON QM-4 AND STS-11B NOZZLES (STS-6A AND STS-6B SHOWED EVIDENCE OF HEATING BUT NOT EROSION)
  - POSTFLIGHT INSPECTION OF JOINTS SHOWS GAS PATH THROUGH PUTTY
  - POSTFLIGHT INSPECTION OF O-RING EROSION INDICATES SHORT TIME, LOCALIZED IMPINGEMENT OF HOT GAS

Chart 28

TECHNICAL ISSUES (CONT)

STS-13 O-RING/VACUUM PUTTY ANALYSIS (CONT)

- MOST PROBABLE MECHANISMS FOR CREATING GAS PATHS ARE:
  - VOID EXISTS IN PUTTY DUE TO AIR ENTRAPMENT DURING JOINT ASSEMBLY
    OR
  - BLOW THROUGH DURING INITIAL LEAK CHECK PRESSURIZATION
    OR
  - LACK OF PUTTY LOCALLY DUE TO JOINT ECCENTRICITY

- RATIONALE FOR ACCEPTING POSSIBILITY OF JOINT O-RING EROSION ON STS-14
  - CONSERVATIVE ANALYSIS INDICATES MAX EROSION POSSIBLE
    0.092 IN (FIELD JOINT)
    0.070 IN (NOZZLE)

  - LABORATORY TEST OF FULL-SCALE O-RING/JOINT CROSS SECTION SHOWS CAPABILITY TO SUSTAIN JOINT SEALING INTEGRITY AT 3,000 PSI PRESSURE USING AN O-RING WITH A SIMULATED 0.095 IN. EROSION DEPTH. THIS DEMONSTRATES A 3 TO 1 SAFETY FACTOR FOR PRESSURE.

- RECOMMENDATION
  - FLY STS-14, ACCEPTING POSSIBILITY OF SOME O-RING EROSION DUE TO HOT GAS IMPINGEMENT

STS 41-G FLIGHT READINESS REVIEWS: Charts 29-32

SRM Preboard (September 12, 1984)

Chart 29

PROBLEM SUMMARY (CONT)
STS-41D PRELIMINARY SRM POSTFLIGHT HARDWARE DAMAGE ASSESSMENT
FIELD JOINTS

PROBLEM	CONCERN	RESOLUTION	TO BE DISCUSSED
RIGHT HAND FORWARD FIELD JOINT PRIMARY O-RING DAMAGED AT 277° WITH MAXIMUM O-RING EROSION DEPTH = 0.026 IN., PERIMETER AFFECTED 100° WITH HEAT AFFECT LENGTH OF 6 INCHES o LABORATORY TEST CONFIRMED THAT O-RING COULD SUSTAIN 0.095 IN. EROSION AND MAINTAIN PRESSURE SEAL AT 3000 PSIA o LESS SEVERE O-RING EROSION THAN SEEN ON STS-2 (0.053 IN.) AND STS-11 (0.040 IN.)	INTEGRITY OF SRM FIELD JOINTS	ACCEPT RISK	NO

Chart 30 -8668

Shuttle Projects Office Board (September 19, 1984)

PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION FOR STS 41–G	TO BE DISCUSSED
– APU FUEL PUMP SEAL CAVITY DRAIN LINE ERODED ON 41–D	FIRST TIME OBSERVED CAUSE NOT APPARENT	EROSION PRECLUDES REUSE ONLY. DOES NOT AFFECT MISSION PERFORMANCE	YES – SPECIAL TOPIC
– RSS ANTENNA DAMAGE	FIRST TIME OBSERVED CAUSED BY DESCENT DEBRIS	NO SRB RSS FUNCTION POST SEPARATION – DAMAGE AFFECTS REUSE ONLY	YES – SPECIAL TOPIC
– REUSE OF SINGLE MISSION QUALIFIED PARTS (41–G)	EXCESSIVE IEA VIBRATION RESPONSE	WAIVER APPROVED; PARTS REFLOWN ON STS 41–D	YES – WAIVER
– CRACK IN I.D. OF BOLT HOLE ON 41–D RIGHT HAND MOTOR STIFFENER STUB	CAPABILITY TO REUSE SEGMENT	(NO PRE-EXISTING CRACKS IN STS 41–D STIFFENER STUBS)	YES – SPECIAL TOPIC
– O RING EROSION OF 0.26 X 6 INCHES ON 41–D RIGHT HAND MOTOR FORWARD FIELD JOINT	INTEGRITY OF JOINT SEAL	– ACCEPTABLE RISK – EROSION LESS THAN STS–2 AND STS–11 – TEST SHOWS MAXIMUM EROSION POSSIBLE LESS THAN EROSION ALLOWABLE (0.95") REF. STS–11 & 13 FRR	NO

Marshall Center Board (September 20, 1984)

Chart 31

SA41–8701

PROBLEM SUMMARY
STS 41-D POST FLIGHT RETREIVAL INSPECTION
SIGNIFICANT OBSERVATIONS

OBSERVATION	CONCERN	RESOLUTION FOR STS 41–G	TO BE DISCUSSED
● ONE OF TWO APU FUEL PUMP SEAL DRAIN LINES ERODED ON L. H. SRB	CATEGORY 3 PREVIOUSLY OBSERVED	USE–AS–IS. MISSION PERFORMANCE NOT AFFECTED.	YES – SPECIAL TOPIC
● O–RING EROSION OF .026 X 6.0 INCHES ON R. H. MOTOR FORWARD SEGMENT FIELD JOINT	CATEGORY 1 INTEGRITY OF JOINT SEAL	USE–AS–IS. MISSION PERFORMANCE NOT AFFECTED. EROSION LESS THAN STS–2 (0.053) AND STS–11 (0.040) AND MUCH LESS THAN ALLOWABLE (0.095)	NO
● 10 EROSION POCKETS ON L. H. SRM NOZZLE	CATEGORY 1 CONTINUED EXPOSURE TO NEGATIVE MARGIN OF SAFETY AT END OF BURN ON NOZZLE INSULATION THICKNESS	USE–AS–IS. STS 41–D RESULTS CONSISTENT WITH EXPECTATIONS UNTIL PLY ANGLE CHANGE MADE.	YES – SPECIAL TOPIC

CATEGORY 1 – MISSION PERFORMANCE
CATEGORY 2 – PRELAUNCH PROCESSING DELAY
CATEGORY 3 – REUSE/TURNAROUND IMPACT

SRB–6

Chart 32

Level I (September 26, 1984)

PROBLEM SUMMARY
STS 41-D POST FLIGHT RETRIEVAL INSPECTION
SIGNIFICANT OBSERVATIONS

OBSERVATION	CONCERN	RESOLUTION FOR STS 41-G	TECHNICAL ISSUE
O-RING EROSION OF .026 X 6.0 INCHES ON R.H. MOTOR FORWARD SEGMENT FIELD JOINT	CATEGORY 1 INTEGRITY OF JOINT SEAL	USE-AS-IS. MISSION PERFORMANCE NOT AFFECTED. EROSION LESS THAN STS-2 (0.053) AND STS-11 (0.040) AND MUCH LESS THAN ALLOWABLE (0.095)	NO

CATEGORY 1 - MISSION PERFORMANCE; CATEGORY 2 - PRELAUNCH PROCESSING DELAY
CATEGORY 3 - RESUSE/TURNAROUND IMPACT

STS 51-E FLIGHT READINESS REVIEWS: Charts 33-81, Transcript

Chart 33

SRM Preboard (January 31, 1985)

FLIGHT READINESS ASSESSMENT FOR STS-51E

- CONCERN
  - STS-51C PRIMARY O-RING EROSION ON TWO FIELD JOINTS
  - STS-51C SOOT BETWEEN PRIMARY AND SECONDARY O-RINGS ON BOTH FIELD JOINTS FIRST TIME OBSERVED ON FIELD JOINT
  - EVIDENCE OF HEAT AFFECT ON SECONDARY O-RING OF A68 (RIGHT HAND) CENTER FIELD JOINT BUT NO EROSION
- CONCLUSION
  - STS-51E COULD EXHIBIT SAME BEHAVIOR
  - CONDITION IS NOT DESIRABLE BUT IS ACCEPTABLE

Chart 34

FLIGHT READINESS ASSESSMENT FOR STS-51E (CONT)

RATIONALE FOR ACCEPTANCE

- O-RING EROSION ON STS-51C WAS WITHIN EXPERIENCE DATA BASE
- MOMENTARY GAS PASSAGE BY THE PRIMARY SEAL WAS SEEN ON THE STS-14A NOZZLE JOINT
- SECONDARY SEAL HEAT EFFECTS WERE WELL BELOW ANALYTICAL WORST CASE PREDICTIONS
- TESTS SHOW THAT O-RINGS WILL SEAL WITH AN EROSION DEPTH OF 0.095 (WHICH IS GREATER THAN THE WORST CASE PREDICTION AND ALMOST TWICE THE EROSION SEEN ON ANY SRM MOTORS).
- PRIMARY O-RING EROSION OBSERVED TO DATE IS ACCEPTABLE AND WILL ALWAYS BE MORE THAN EROSION ON SECONDARY O-RING IF IT OCCURS.
  - PRIMARY O-RING LEAK CHECK PUSHES O-RING IN WRONG DIRECTION -- SECONDARY O-RING IS SEATED BY LEAK CHECK
  - GAS VOLUME IN FRONT OF PRIMARY O-RING IS 50% GREATER THAN FREE VOLUME BETWEEN O-RINGS
  - GAS WILL COOL AS IT PASSES PRIMARY O-RING
- STS-51E FIELD JOINTS ARE ACCEPTABLE FOR FLIGHT

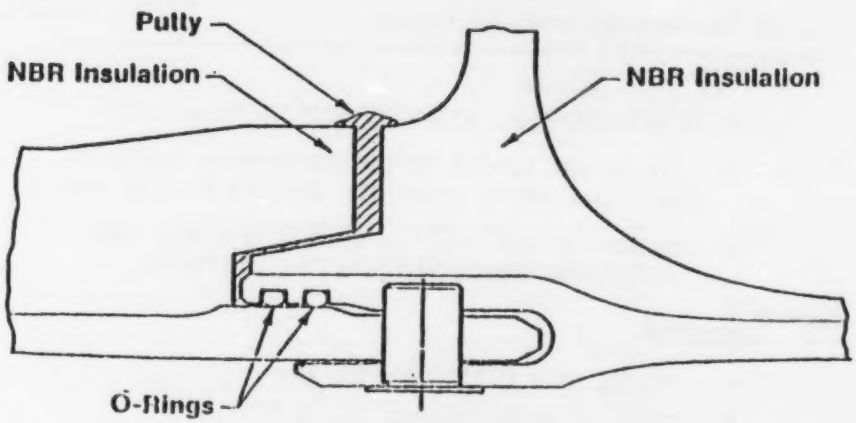
Chart 35

TECHNICAL ISSUES

- O-RING EROSION ON STS-20A (STS-51C), (SRM-15) FORWARD FIELD JOINT AND ON STS-20B, (STS-51C), (SRM-15) CENTER FIELD JOINT
  - ACCEPTANCE OF O-RING EROSION
  - TWO OCCURRENCE ON THE SAME FLIGHT WITH SOOT BEHIND THE PRIMARY O-RING

Chart 36

TECHNICAL ISSUES (CONT)



SRM-HPM Field Joint

Chart 37

TECHNICAL ISSUES (CONT)

- SRM O-RING JOINT (TANG & CLEVIS) DESIGN PARAMETERS
  - DATA USING WORST CASE DESIGN DIMENSIONS
  - MINIMUM O-RING SQUEEZE 0.020-INCH (7.54%)
    - MINIMUM O-RING EFFECTIVE DIAMETER 0.269-INCH
  - MAXIMUM O-RING SQUEEZE 0.066-INCH (23.97%)
    - MAXIMUM O-RING EFFECTIVE DIAMETER 0.275-INCH
  - MAXIMUM GAP DIMENSION 0.065-INCH
  - MINIMUM GAP DIMENSIONS 0.035-INCH
  - BOTH ABOVE GAPS MODIFIED BY USING A 0.032-INCH MIN SHIM

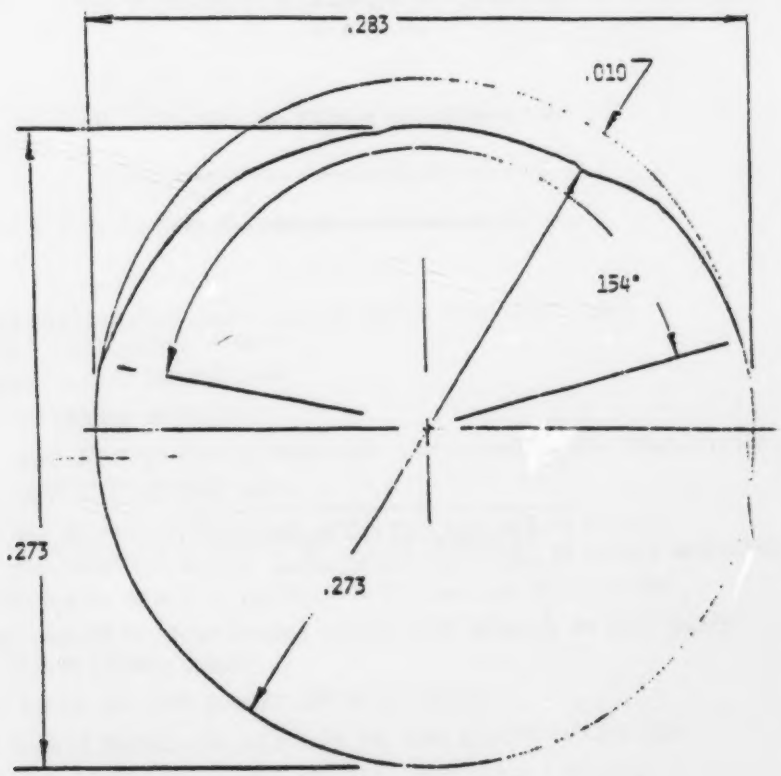
PRELIMINARY POSTFLIGHT HARDWARE DAMAGE ASSESSMENT (CONT)

A07 (LEFT FORWARD FIELD JOINT) (CONT)

- PRIMARY O-RING SOOTED AT INTERFACE WITH GROOVE ON UPSTREAM SIDE
- EROSION ON PRIMARY O-RING DIFFICULT TO SEE WITH O-RING IN GROOVE
  - O-RING EROSION SURFACE LOOKED ONLY SLIGHTLY ROUGHENED
- SOOT IN THE PRIMARY GROOVE ON THE DOWNSTREAM SIDE
- SOOT TOTALLY COVERED THE GREASE ON THE LAND BETWEEN THE O-RINGS
- GREASE WAS SOOTED (BLACKENED) BUT STILL WAS GREASY - NOT HARD
- BOTTOM AND AFT FACE OF SECONDARY GROOVE HAD CLEAN GREASE
- CLEVIS SURFACE AFT OF SECONDARY O-RING HAD CLEAN GREASE
- NO SECONDARY O-RING BLOW-BY WAS OBSERVED

Chart 39

SRM-15A FWD PRIMARY SEAL



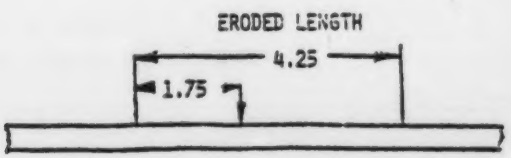
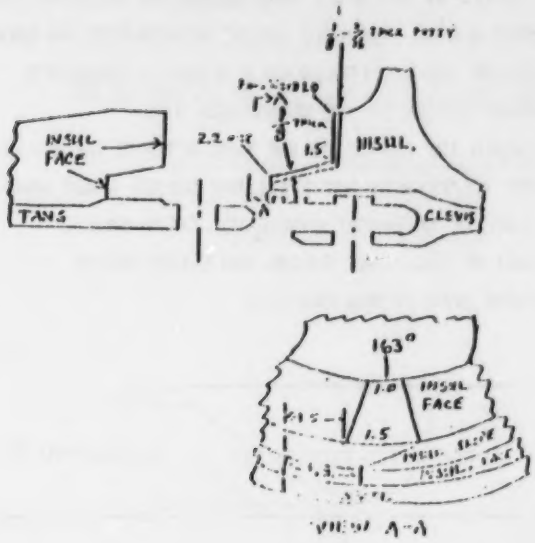


Chart 40

STS-51C (STS-20) (SRM-15) PERFORMANCE (CONT)

PRELIMINARY POSTFLIGHT HARDWARE DAMAGE ASSESSMENT (CONT)



AFT FORWARD FIELD JOINT GAS PATH (STS-51C)

Chart 41

5 Photographs - Not Reproducible

Chart 42

STS-51C (STS-20) (SRM-15) TECHNICAL ISSUES (CONT)

PRELIMINARY POSTFLIGHT HARDWARE DAMAGE ASSESSMENT (CONT)

A68 (RIGHT CENTER FIELD JOINT)

- GAS PATH THRU PUTTY AND PAST PRIMARY O-RING AT 354°
- CLEVIS PUTTY (T = 1/8 INCH) STILL SOFT WITH LIGHT CHAR AND SOOT AT 354°
- SOOTED ARC ON TANG SEAL SURFACE AND INSUL. FACE 320° - 0° - 10°
- BLACK GREASE (SOOTED) BETWEEN O-RINGS 282° - 0° - 32°
- SEE FIGURE FOR PATH DESCRIPTION
- PRIMARY O-RING EROSION
  - EROSION 12.5 INCH CIRC
  - HEAT AFFECTED 58-3/4-INCH CIRC
  - APPROXIMATELY 120° ARC OF CROSS SECTION ERODED
  - NOMINAL CROSS SECTION .278 INCH (NON-ERODED)
  - MAX EROSION SECTION .240 INCH
  - TOTAL EROSION DEPTH 0.038 INCH
  - MEASUREMENTS WITH AN OPTICAL COMPARATOR

Chart 43

STS-51 C (STS-20) (SRM-15) TECHNICAL ISSUES (CONT)

PRELIMINARY POSTFLIGHT HARDWARE DAMAGE ASSESSMENT (CONT)

A68 (RIGHT CENTER FIELD JOINT) (CONT)

- SECONDARY O-RING OBSERVATIONS
  - NO EROSION ON O-RING
  - HEAT AFFECTED ZONE 18 INCH CIRC - APPROXIMATELY 60° CROSS SECTION ARC
  - HEAT AFFECTED ZONE BASIS
    - DIFFERENCE IN SURFACE APPEARANCE W/O LOSS OF MATERIAL
    - SECONDARY O-RING ON A67 HAD NO DIFFERENCE IN SURFACE APPEARANCE
- PRIMARY O-RING SOOTED AT INTERFACE WITH GROOVE ON UPSTREAM SIDE
- O-RING EROSION WAS VERY OBVIOUS AND WAS SEEN ADJACENT TO THE FORWARD HALL OF THE PRIMARY GROOVE
  - O-RING MAY HAVE ROTATED DURING DISASSEMBLY
- SOOT TOTALLY COVERED THE GREASE ON THE LAND BETWEEN THE O-RINGS
- GREASE HAS SOOTED (BLACKENED) BUT STILL HAS GREASY - NOT HARD
- BOTTOM AND AFT FACE OF SECONDARY GROOVE HAD CLEAN GREASE
- CLEVIS SURFACE AFT OF SECONDARY O-RING HAD CLEAN GREASE
- NO SECONDARY O-RING BLOW-BY WAS OBSERVED

Chart 44

SRM-15B CTR PRIMARY SEAL

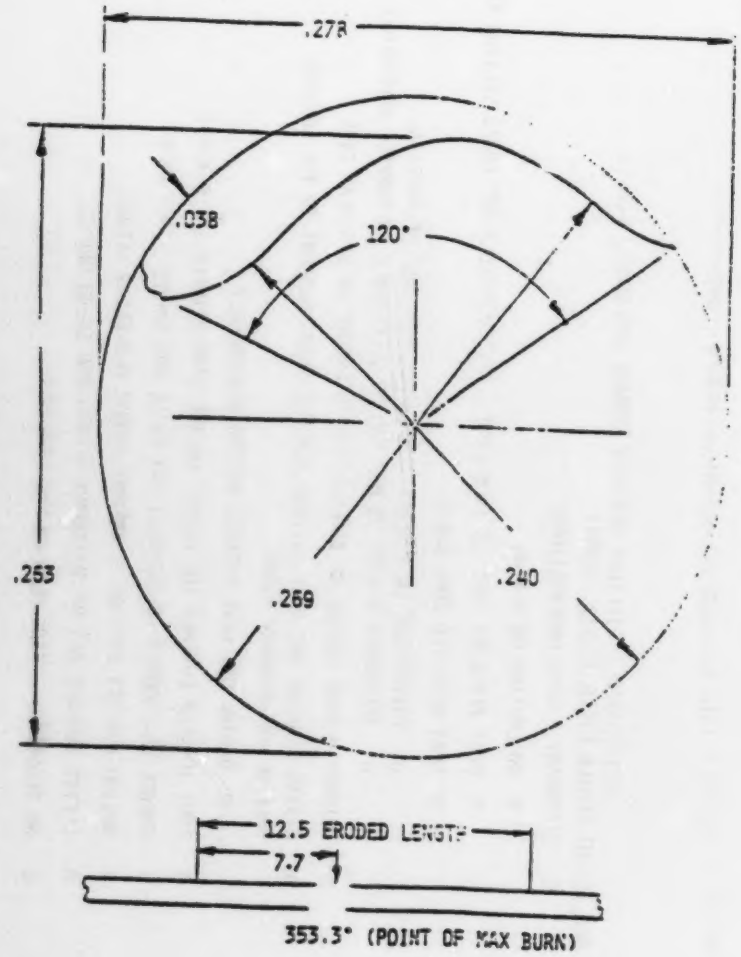


Chart 45

SRM-15 B CTR SECONDARY SEAL

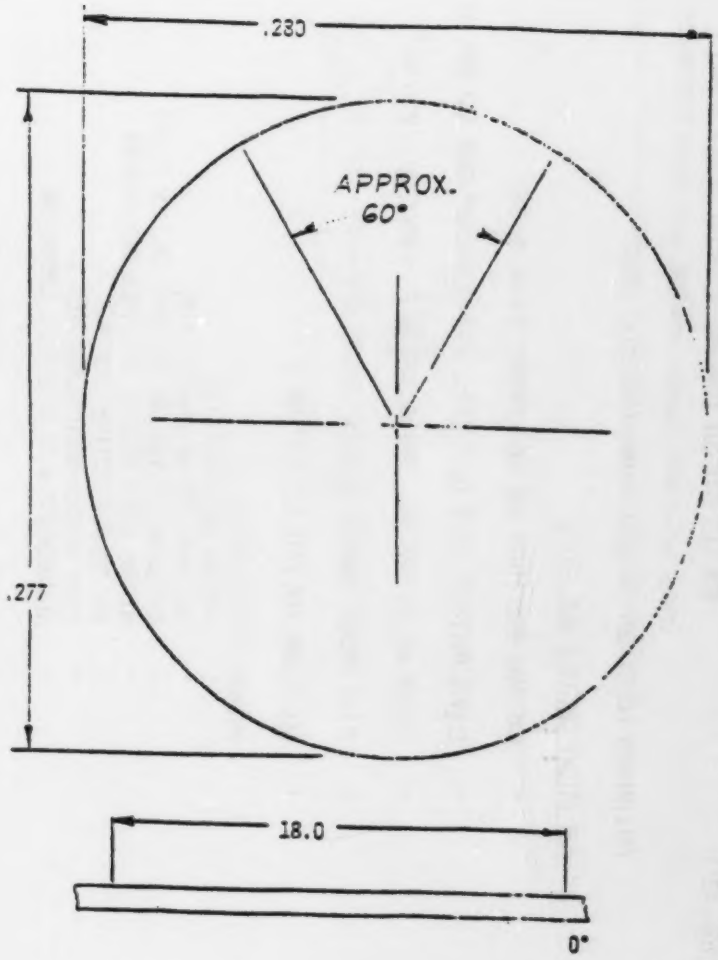
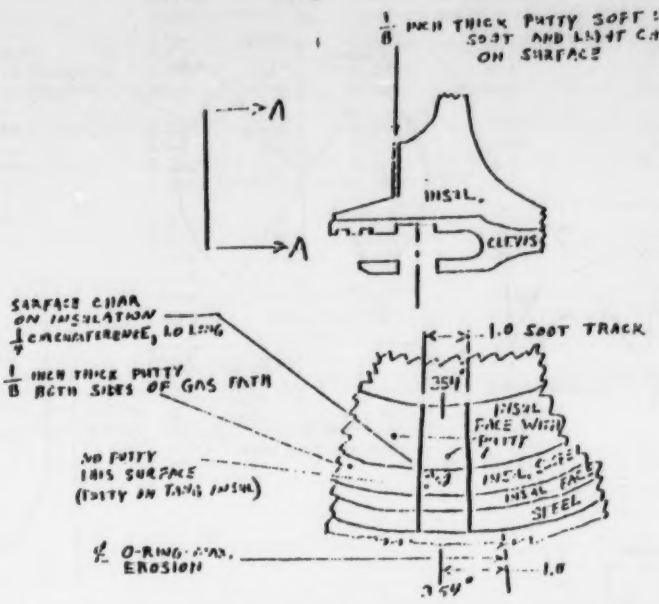


Chart 46

PRELIMINARY POSTFLIGHT HARDWARE DAMAGE ASSESSMENT (CONT)



AGB RIGHT CENTER FIELD JOINT GAS PATH (STS-51C)

Chart 47

2 Photographs - Not Reproducible

Chart 48

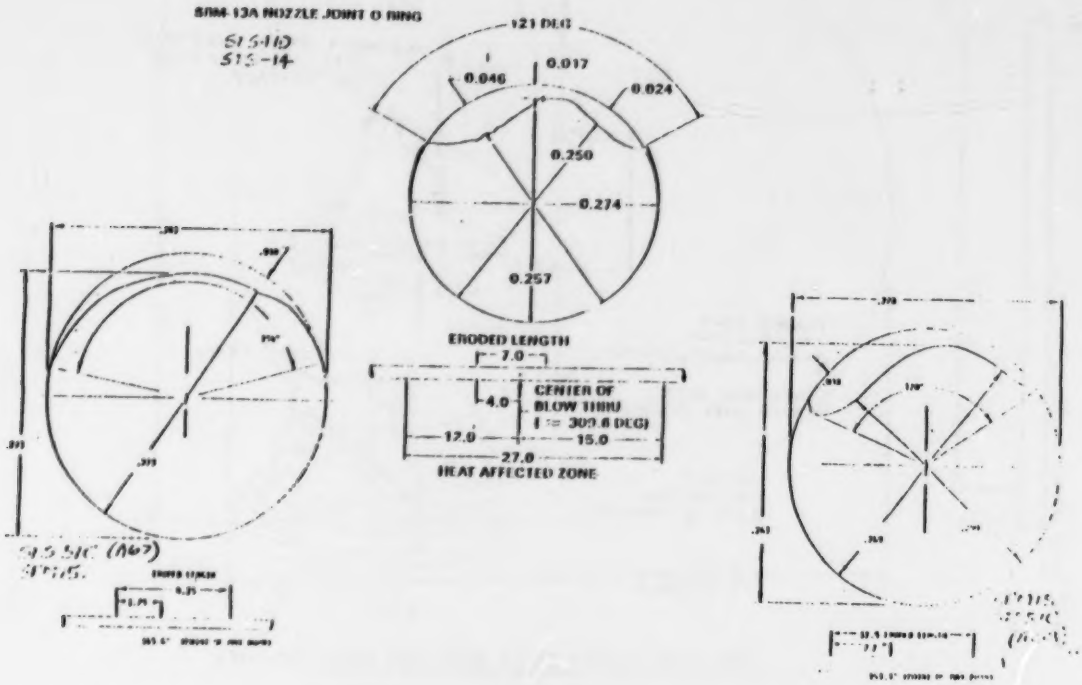


Chart 49

TECHNICAL ISSUES (CONTINUED)

- Analysis of Soot from STS-51C LH Forward Field

	Primary Groove Sample	Land Between O Rings	Tang Sample	Clevis Sample	
				Black Putty	Green Putty
FTIR	HD-2, Water	HD-2, Water	HD-2, Water	Polyester,	Polyester
Note: No HB Polymer No Fluorocarbon detected			Polyester (Putty)	Water	Water
EDAX*					
Fluoride (O-ring)	Present	Trace	Present	None	None
Sodium (Grease)	Present	Present	Present	Small Trace	Small Trace
Magnesium (Asebestos, putty)	Present	Present	Minor	Major	Major
Aluminum (Propellant)	Major	Minor	Major	Present	Trace
Silicon (Asbestos, putty)	Present	Present	Minor	Major	Major
Chloride (Propellant AP or Sea Water)	Major	Major	Minor	Present	None
Calcium (Grease)	Major	Major	Major	None	None
Sulfur (Grease)	Minor	Minor	Minor	None	None
Fluoride Ion Test (120%)	0.8%	1.47%	2.1%	0.64%	

* Relative amounts detected, starting with greatest
Major
Minor
Present
Trace
None

Chart 50

- HISTORY OF SRM O-RING DAMAGE

	Cross-Sectional View			Top View	
	Erosion Depth (in.)	Perimeter Affected (deg.)	Nominal Diameter (in.)	Length of Maximum Erosion (in.)	Total Heat Affected Length (in.)
STS-20A Fwd Field**	0.010	154	0.280	4.25	5.25
STS-20B Cen Field (Prim)***	0.038	120	0.280	12.5	58.75
STS-20B Cen Field (Sec)***	None	45	0.280	None	29.5
STS-14B Fwd Field	0.028	110	0.280	3.0	None
STS-13A Aft Field*	None	None	0.280	None	None
STS-11A Fwd Field	0.040	217	0.280	3.0	14.5
STS-2B Aft Field	0.053	116	0.280	--	--
STS-14A Nozzle**	0.046	121	0.275	4.0	7.0
STS-13B Nozzle	0.034	136	0.275	1.8	5.6
STS-11B Nozzle	0.039	103.5	0.275	0.75	45
QM-4 Nozzle	0.051	101	0.275	5	11
STS-6A Nozzle*	None	None	0.275	None	None
STS-6B Nozzle*	None	None	0.275	None	None

---

* Hot gas path detected in putty. Indication of heat on O-ring, but no damage.
** Soot behind primary o-ring.
*** Soot behind primary o-ring, heat affected secondary o-ring

Chart 51

- COMPARISON OF STS-51-C AND STS-51-E
  - NO PROBLEMS ENCOUNTERED WITH PUTTY LOT NUMBERS OR INSTALLATION ON ALL FIELD JOINTS
  - NO ANOMALOUS CONDITIONS AT ASSEMBLY OF:
    - O-RINGS
    - GREASE
    - LEAK CHECK
      - ALL STS-51-C AND STS-51-E (SRM-16) FIELD JOINTS PASSED LEAK CHECK WITH A DECAY OF 0.2 PSI OR LESS, FIRST ATTEMPT. (1.0 PSI LEAKAGE ALLOWED DURING 10 MINUTE PERIOD AT 50 PSIG.)

Chart 52
TECHNICAL ISSUES (CONT)

SCENARIO

- O-RING ACTUATION SCENARIO IS THE SAME FOR FIELD JOINTS AND NOZZLE JOINTS
- FREE VOLUME IS CREATED BY DESIGN; VACUUM PUTTY LAYUP, O-RING GROOVE AND O-RING SQUEEZE AND CLEARANCES BETWEEN MATING PARTS
- FLOW PATH CAN BE CREATED BY JOINT ASSEMBLY, O-RING LEAK CHECK AND/OR PUTTY BLOW-BY DURING MOTOR IGNITION AND INITIAL PRESSURIZATION
- FLOW PATH LEADS TO THE FREE VOLUME FILLING PROCESS WHICH INDUCES LOCALIZED SHORT TIME DURATION HOT GAS JET IMPINGEMENT ON THE O-RING WITH THE ASSOCIATED HIGH STAGNATION POINT HEATING; PROCESS CONTINUES ONLY UNTIL THE FREE VOLUME IS FILLED AND PRESSURE EQUALIZATION IS ACHIEVED
- TEST DATA INDICATES THAT VITON RUBBER (UNFILLED FLUOROCARBON) EXHIBITS VERY HIGH EROSION RATES (> 200 MILS/SEC) DEPENDING UPON THE HEAT TRANSFER COEFFICIENT

Chart 53
TECHNICAL ISSUES (CONT)

- VOLUMETRIC AND THERMAL ANALYSIS AND TEST RESULTS

	MAXIMUM EXPECTED EROSION	MAXIMUM EROSION EXPERIENCED
FIELD JOINT		
PRIMARY	0.092	0.053
SECONDARY	0.060	NONE*
NOZZLE JOINT		
PRIMARY	0.070	0.051
SECONDARY	0.004	NONE

*HEAT EFFECTS WITH NO DEPTH SEEN ON STS-20B

- TESTS SHOW THAT O-RING MAINTAINS SEAL UNDER 3000 PSI WHEN 0.095 INCH MATERIAL IS REMOVED, A 3:1 SAFETY FACTOR FOR PRESSURE EXTRUSION
- SOOT SEEN BEHIND STS-51A NOZZLE PRIMARY SEAL WAS A RESULT OF MOMENTARY GAS PASSAGE BEFORE THE O-RING SEATED

Chart 54

SIS 51C (SRM-15) SIS-20 O RING EROSION SCENARIO

A 0 NO EROSION UNTIL SONIC FLOW ESTABLISHED IN FIELD JOINT AREA (0 - 50 PSI)

B 0 PRIMARY O-RING SEATING PHASE (50 - 200 PSI)

- 0 LOW TEMPERATURE SHRINKS O-RING AND INCREASES DURometer
- 0 GAS JET THROUGH PUTTY IMPINGES ON PRIMARY O-RING
- 0 INITIAL EROSION OF PRIMARY O-RING OCCURS (< 10 MILS)
- 0 GAS FLOW PAST PRIMARY O-RING OCCURS
  - 0 O-RING PRODUCTS FOUND IN SOOT
  - 0 PUTTY PRODUCTS FOUND IN SOOT
- 0 GAS FLOW DEPOSITS SOOT AND LOSES HEAT (ΔT = 525°F) IN CIRCUMFERENTIAL EXPANSION BETWEEN O-RINGS, ΔT = 570°F BETWEEN O-RINGS
- 0 NO DAMAGE TO SECONDARY O-RING

Chart 55

SIS 51C (SRM-15) SIS-20 O-RING EROSION SCENARIO (CONT)

C 0 PRIMARY O-RING SEALS AND CONTINUES TO ERODE

- 0 PRIMARY O RING SEATS BY THE TIME PRESSURE REACHES 200 PSI
- 0 FREE VOLUME INCREASES 10X FROM POINT "A" TO POINT "C" DUE TO MOTOR PRESSURIZATION AND JOINT EXPANSION
- 0 MAJORITY OF O-RING EROSION OCCURS DURING THIS PHASE UNTIL PRESSURE EQUILIBRATION OCCURS AT APPROXIMATELY 330MS
- 0 DEPTH OF EROSION IS A FUNCTION OF GAS JET SIZE I.E. SMALLER SIZE HIGHER EROSION
- 0 A67 (L.H.) GAS PATH 2.2 INCHES NEAR O-RING COMPARED TO 1.0 INCH ON A68 (R.H.) I.E. AREA RATIO = 4.8, EROSION DEPTH RATIO = 3.8, ASSUMING FINAL AREA SAME RATIO AS INITIAL

Chart 56

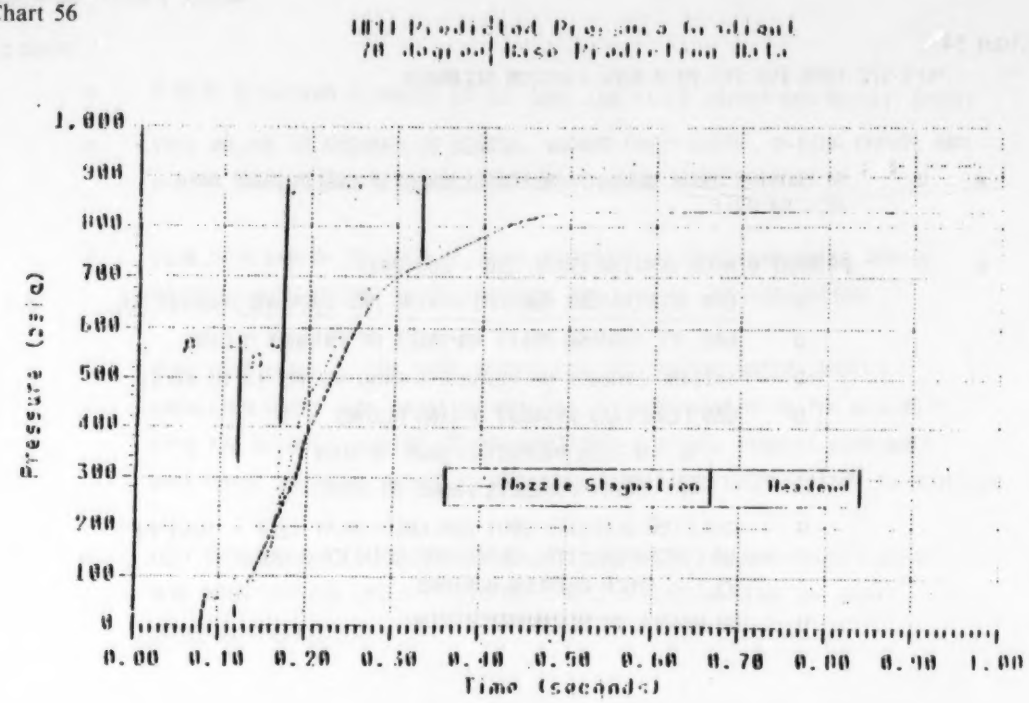
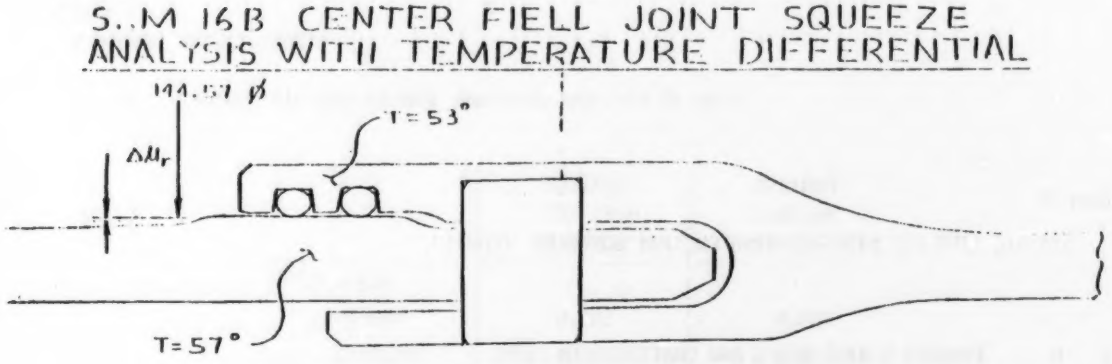


Chart 57



ΔT ACROSS SEALING SURFACE = 4°

$$\Delta M_r = \frac{\alpha D \Delta T}{2} = \frac{6.3(10^{-6})\,144.57\,(4)}{2} = 0.0018''$$

SQUEEZE WITH TEMPERATURE DIFFERENTIAL

PRIMARY
@ 13% INITIAL STATIC
SQUEEZE = (.13(0.273) − 0.0018) = 0.0337" = 12.3%

SECONDARY
@ 4.8% INITIAL AT PRESSURE
SQUEEZE = (0.048(0.273) − 0.0018) = 0.0113" = 4.1%

NOTE: AT BASED ON TEMPERATURE CYCLE WITH UNIFORM TEMPERATURE AT 45°F AND AMBIENT TEMPERATURE RAISED TO 64°F

@ O-RING SQUEEZE MAINTAINED FOR THE 4°F Δ T CONDITION

Chart 58

TECHNICAL ISSUES

- TEMPERATURE EFFECTS
  - THERMAL ANALYSIS SHOWS THAT THE SRM FOLLOWS DAILY TEMPERATURES TO A DEPTH OF FIVE INCHES
  - PUTTY BECOMES STIFFER AND LESS TACKY
  - O-RING BECOMES HARDER
    - A VITON O-RING WITH 70 DUROMETER AT 70°F CAN INCREASE TO 85 DUROMETER AT 20°F
    - TEMPERATURE PRIOR TO FLIGHT DROPPED TO 17°F
    - TEMPERATURE SQUEEZE REDUCED BY ~1% DUE TO A 4°F DELTA

Chart 59

FLIGHT READINESS ASSESSMENT FOR STS-51E (CONT)

RATIONALE FOR ACCEPTANCE

- O-RING EROSION ON STS-51-C WAS WITHIN EXPERIENCE DATA BASE
- MOMENTARY GAS PASSAGE BY THE PRIMARY SEAL WAS SEEN ON THE STS-14A NOZZLE JOINT
- SECONDARY SEAL HEAT EFFECTS WERE WELL BELOW ANALYTICAL WORST CASE PREDICTIONS
- GAS JET PENETRATES THE PRIMARY SEAL PRIOR TO ACTUATION AND SEALING
- TESTS SHOW THAT O-RINGS WILL SEAL AT 3,000 PSI WITHIN 0.095 INCH OF MISSING MATERIAL (WHICH IS GREATER THAN THE WORST CASE PREDICTION AND ALMOST TWICE THE EROSION SEEN ON ANY SRM MOTORS).
- PRIMARY O-RING EROSION OBHSERVED TO DATE IS ACCEPTABLE AND WILL ALWAYS BE MORE THAN EROSION ON SECONDARY O-RING IF IT OCCURS.
  - PRIMARY O-RING LEAK CHECK PUSHES O-RING IN WRONG DIRECTION -- SECONDARY O-RING IS SEALED BY LEAK CHECK
  - GAS VOLUME IN FRONT OF PRIMARY O-RING IS 50% GREATER THAN FREE VOLUME BETWEEN O-RINGS
  - GAS WILL COOL AS IT PASSES PRIMARY O-RING AND DIFFUSES CIRCUMFERENTIALLY
- SECONDARY O-RING IS A REDUNDANT SEAL USING ACTUAL HARDWARE DIMENSIONS

Chart 60

FLIGHT READINESS ASSESSMENT FOR STS-51E (CONT)

- EVALUATION SUMMARY
  - STA-51-C PRIMARY O-RING EROSION ON TWO FIELD JOINTS
  - STS-51-C SOOT BETWEEN PRIMARY AND SECONDARY O-RINGS ON BOTH FIELD JOINTS -- FIRST TIME OBSERVED ON FIELD JOINT
  - EVIDENCE OF HEAT AFFECT ON SECONDARRY O-RING OF A68 (RIGHT HAND) CENTER FIELD JOINT BUT NO EROSION
- CONCLUSION
  - STS-51-C CONSISTENT WITH EROSION DATA BASE
    - LOW TEMPERATURE ENHANCED PROBABILITY -- STS-51-C EXPERIENCED WORST CASE TEMPERATURE CHANGE IN FLORIDA HISTORY
    - EROSION IN TWO JOINTS OBSERVED BEFORE -- STS-11 AND -14
  - STS-51-E COULD EXHIBIT SAME BEHAVIOR
  - CONDITION IS ACCEPTABLE
- STS-51-E FIELD JOINTS ARE ACCEPTABLE FOR FLIGHT

Shuttle Projects Office Board (February 12, 1985)

Chart 61

A41-9174

SUMMARY OF ACTION ITEMS

ACTION	DESCRIPTION	STATUS	REMARKS
SRM 1	PROVIDE SRM EXIT CONE ENVIRONMENT FOR DESCENT	CLOSED	AEROTHERMAL & ACOUSTIC ENVIRONMENT PROVIDED TO MTI FOR ANALYSIS OF EXIT CONE BREAKUP
SRM 2	PROVIDE THE DESIGN MARGIN OF SAFETY OF NOZZLE EXTENSION FOR ASCENT FLIGHT	CLOSED	SPECIAL TOPIC
SRM 3	PROVIDE ADDITIONAL DATA REGARDING SIC CASE JOINT O-RING EROSION	CLOSED	SPECIAL TOPIC
SRM 4	EXPAND DM-7 FWC INSULATION DEBOND RATIONALE RE: STEEL CASES	CLOSED	SPECIAL TOPIC
SRM 5	EXPAND RATIONALE RE: NOZZLE EXIT CONE FAILURE TO DEFINE THE ENVIRONMENT THAT CAUSED FAILURE	CLOSED	SPECIAL TOPIC
SRM 6	EXPAND STS 51-C O-RING EROSION RATIONALE RE: INTEGRITY OF SECONDARY SEAL	CLOSED	SPECIAL TOPIC

Chart 62

PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION	SPECIAL TOPIC
• EVIDENCE OF HOT GAS PAST PRIMARY O-RINGS ON 2 CASE JOINTS (PREVIOUSLY OBSERVED ON NOZZLE JOINT)	MISSION SAFETY	ACCEPTABLE RISK BECAUSE OF LIMITED EXPOSURE AND REDUNDANCY (REF. STS 41-C FRR)	YES
• DM-7 FWC HAS A DELAMINATION IN THE INTERNAL INSULATION WHICH COULD BE THE RESULT OF A GENERIC PROCESS PROBLEM COMMON TO STEEL CASES	MISSION SAFETY	FWC UNIQUE	YES
• BREAKUP OF -403 AND -404 RINGS IN LEFT HAND SRM EFFECT ON ABILITY TO EVALUATE NOZZLE EROSION	MISSION SAFETY	RECONSTRUCTION VERIFIES NOMINAL EROSION	YES
• DIMENSIONAL DISCREPANCY ON STS 51-E LEFT HAND NOZZLE RESULTS IN LESS THAN SPECIFIED MINIMUM O-RING SQUEEZE	MISSION SAFETY	ACCEPTABLE RISK, WITHIN SUCCESSFUL TEST AND FLIGHT EXPERIENCE BASE	YES
• APU SN 149 FUEL PUMP SHAFT SEAL LEAK OUT-OF-SPEC	MISSION SAFETY	REMOVED, RETESTED, REINSTALLED, TEST O.K.	NO
• AFT BSM/SN 1000045 DAMAGED BY FRANGIBLE NUT PRE-TENSIONER DEBRIS	MISSION SAFETY	REMOVE & REPLACE 1V/SN1000060	NO
• APU CONTROLLER CAPACITOR FAILURES ON ORBITER APU	MISSION SAFETY	CHANGE OUT AFT IEA'S	YES

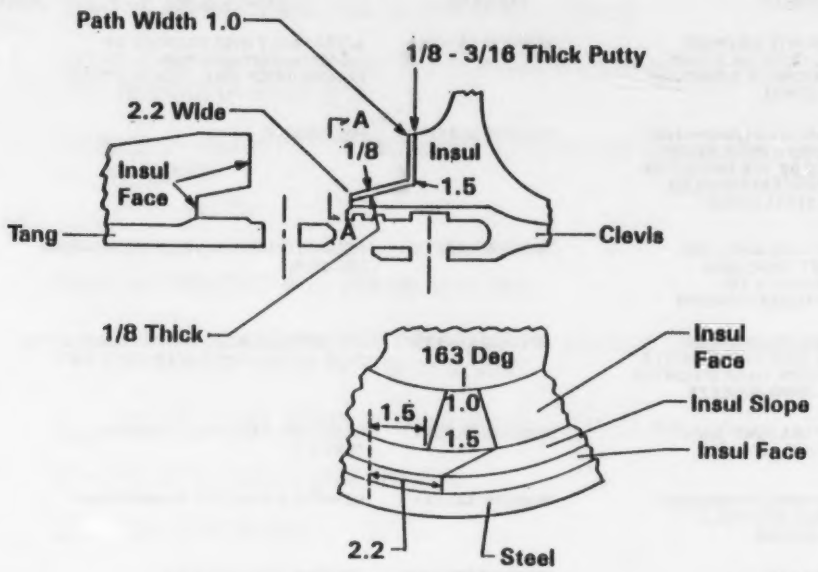
Chart 63

STS-51C (SRM-15) POSTFLIGHT HARDWARE DAMAGE ASSESSMENT

- A67 (LEFT FORWARD FIELD JOINT)
  - GAS PATH THRU PUTTY AND PAST PRIMARY O-RING AT 163°
  - HARD THIN CHAR ON TANG INSULATION AT 163°
  - CHAR ON CLEVIS PUTTY STILL SOFT (T = 1/8 - 3/16 INCH) AT 163°
  - SOOTED ARC ON TANG SEAL SURFACE AND INSUL. FACE 124° TO 188°
  - BLACK GREASE (SOOTED) BETWEEN O-RINGS 150° TO 230°
  - PRIMARY O-RING SOOTED AT INTERFACE WITH GROOVE ON UPSTREAM SIDE
  - SOOT IN THE PRIMARY GROOVE ON THE DOWNSTREAM SIDE
  - SOOT TOTALLY COVERED THE GREASE ON THE LAND BETWEEN THE O-RINGS
  - GREASE WAS SOOTED (BLACKENED) BUT STILL WAS GREASY - NOT HARD
  - BOTTOM AND AFT FACE OF SECONDARY GROOVE HAD CLEAN GREASE
  - CLEVIS SURFACE AFT OF SECONDARY O-RING HAD CLEAN GREASE
  - NO SECONDARY O-RING BLOW-BY WAS OBSERVED

Chart 64

STS-51C (STS-20) (SRM-15) Performance
Preliminary Postflight Hardware Damage Assessment



View A-A
A67 Forward Field Joint Gas Path (STS-51C)

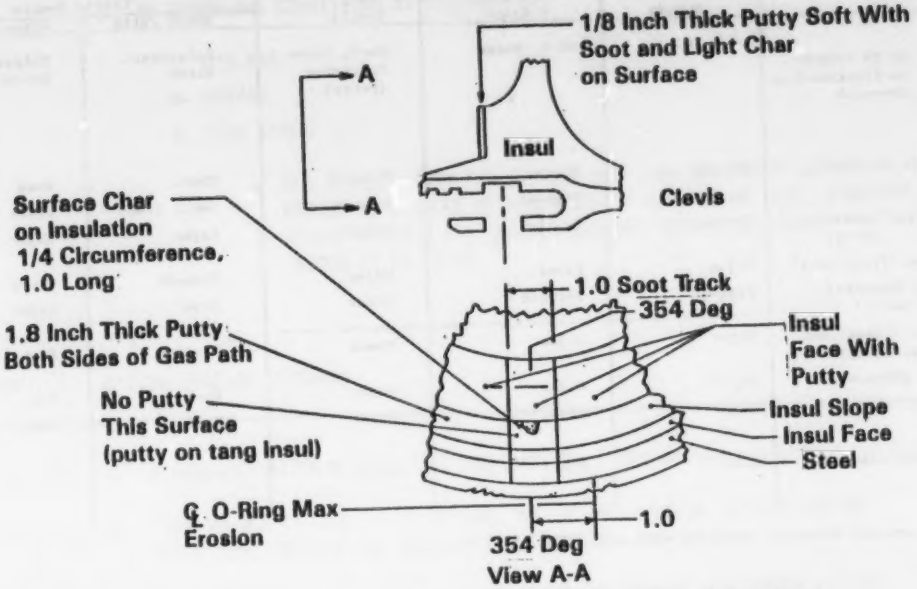
Chart 65

STS-51C (SRM-15) POSTFLIGHT HARDWARE DAMAGE ASSESSMENT (CONT)

- A68 (RIGHT CENTER FIELD JOINT)
  - GAS PATH THRU PUTTY AND PAST PRIMARY O-RING AT 354°
  - CLEVIS PUTTY (T = 1/8 IN.) STILL SOFT WITH LIGHT CHAR AND SOOT AT 354°
  - SOOTED ARC ON TANG SEAL SURFACE AND INSULATION FACE 320° - 0° - 10°
  - BLACK GREASE (SOOTED) BETWEEN O-RINGS 282° - 0° - 32°
  - PRIMARY O'RING SOOTED AT INTERFACE WITH GROOVE ON UPSTREAM SIDE
  - O'RING EROSION WAS VERY OBVIOUS AND WAS SEEN ADJACENT TO THE FORWARD WALL OF THE PRIMARY GROOVE
  - SOOT TOTALLY COVERED THE GREASE ON THE LAND BETWEEN THE O'RINGS
  - GREASE WAS SOOTED (BACKENED) BUT STILL WAS GREASY - NOT HARD
  - SECONDARY O'RING OBSERVATIONS
    - NO EROSION ON SECONDARY O'RING
    - HEAT AFFECTED ZONE 18 IN. CIRC - APPROXIMATELY 60° CROSS SECTION ARC
    - HEAT AFFECTED ZONE BASIS
      - DIFFERENCE IN SURFACE APPEARANCE W/O LOSS OF MATERIAL
      - SECONDARY O'RING ON A67 HAD NO DIFFERENCE IN SURFACE APPEARANCE
    - BOTTOM AND AFT FACE OF SECONDARY GROOVE HAD CLEAN GREASE
    - CLEVIS SURFACE AFT OF SECONDARY O'RING HAD CLEAN GREASE
    - NO SECONDARY O'RING BLOW-BY WAS OBSERVED

Chart 66

STS-51C (STS-20) (SRM-15) Performance
Preliminary Postflight Hardware Damage Assessment



A68 Right Center Field Joint Gas Path (STS-51C)

Chart 67

O-Ring Erosion Patterns

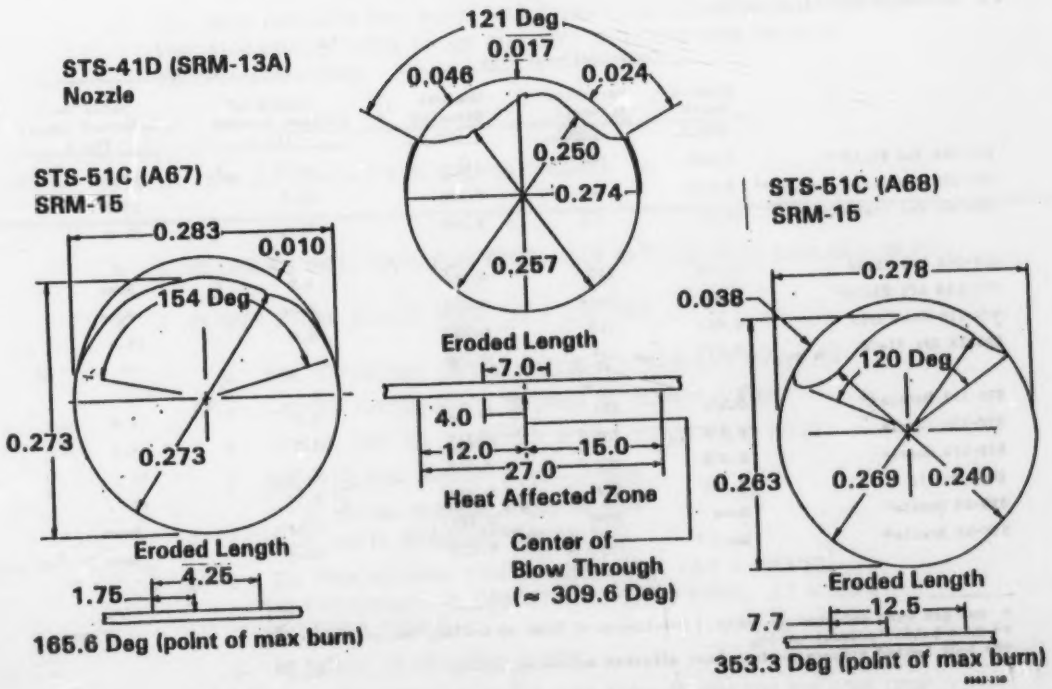


Chart 68

- Analysis of Soot from STS-51C LH Forward Field Joint

	Primary Groove Sample	Land Between O-Rings	Tang Sample	Clevis Sample	
				Black Putty	Green Putty
FTIR Note: No HB Polymer, No Fluorocarbon detected	HD-2, Water	HD-2, Water	HD-2, Water Polyester (Putty)	Polyester, Water	Polyester, Water
EDAX[a]					
Fluoride (O-ring)	Present	Trace	Present	None	None
Sodium (Grease)	Present	Present	Present	Small Trace	Small Trace
Magnesium (Asbestos, putty)	Present	Present	Minor	Major	Major
Aluminum (Propellant)	Major	Minor	Major	Present	Trace
Silicon (Asbestos, putty)	Present	Present	Minor	Major	Major
Chloride (Propellant AP or Sea Water)	Major	Major	Minor	Present	None
Calcium (Grease)	Major	Major	Major	None	None
Sulfur (Grease)	Minor	Minor	Minor	None	None
Fluoride Ion Test (±20%)	0.8%	1.47%	2.1%	0.64%	-

[a]Relative amounts detected, starting with greatest
Major
Minor
Present
Trace
None

Chart 69

- HISTORY OF SRM O-RING DAMAGE

	Cross-Sectional View			Top View	
	Erosion Depth (in.)	Perimeter Affected (deg)	Nominal Diameter (in.)	Length of Maximum Erosion (in.)	Total Heat Affected Length (in.)
STS-20A Fwd Field[aa]	0.010	154	0.280	4.25	5.25
STS-20B Cen Field (Prim)[aaa]	0.038	120	0.280	12.5	58.75
STS-20B Cen Field (Sec)[aaa]	None	45	0.280	None	29.5
STS-14B Fwd Field	0.028	110	0.280	3.0	None
STS-13A Aft Field[a]	None	None	0.280	None	None
STS-11A Fwd Field	0.040	217	0.280	3.0	14.5
STS-2B Aft Field	0.053	116	0.280	---	---
STS-14A Nozzle[aa]	0.046	121	0.275	4.0	7.0
STS-13B Nozzle	0.034	136	0.275	1.8	5.6
STS-11B Nozzle	0.039	103.5	0.275	0.75	45
QM-4 Nozzle	0.051	101	0.275	5	11
STS-6A Nozzle[a]	None	None	0.275	None	None
STS-6B Nozzle[a]	None	None	0.275	None	None

[a] Hot gas path detected in putty. Indication of heat on O-ring, but no damage.
[aa] Soot behind primary o-ring
[aaa] Soot behind primary o-ring, heat affected secondary o-ring

Chart 70 COMPARISON OF STS-51C AND STS-51E

- NO PROBLEMS ENCOUNTERED WITH PUTTY LOT NUMBERS OR INSTALLATION ON ALL FIELD JOINTS
- NO ANOMALOUS CONDITIONS AT ASSEMBLY OF:
  - O'RINGS
  - GREASE
  - LEAK CHECK
    - ALL STS-51C (SRM-15) AND STS-51E (SRM-16) FIELD JOINTS PASSED LEAK CHECK WITH A DECAY OF 0.2 PSI OR LESS, FIRST ATTEMPT. (1.0 PSI LEAKAGE ALLOWED DURING 10 MINUTE PERIOD AT 50 PSIG)

Chart 71 O'RING EROSION SCENARIO

- O'RING ACTUATION SCENARIO IS THE SAME FOR FIELD JOINTS AND NOZZLE JOINTS
- FREE VOLUME IS CREATED BY DESIGN, VACUUM PUTTY LAYUP, O'RING GROOVE AND O'RING SQUEEZE AND CLEARANCES BETWEEN MATING PARTS
- FLOW PATH CAN BE CREATED BY JOINT ASSEMBLY, O'RING LEAK CHECK AND/OR PUTTY BLOW-BY DURING MOTOR IGNITION AND INITIAL PRESSURIZATION
- FLOW PATH LEADS TO THE FREE VOLUME FILLING PROCESS WHICH INDUCES LOCALIZED SHORT TIME DURATION HOT GAS JET IMPINGEMENT ON THE O'RING WITH THE ASSOCIATED HIGH STAGNATION POINT HEATING, PROCESS CONTINUES ONLY UNTIL THE FREE VOLUME IS FILLED AND PRESSURE EQUALIZATION IS ACHIEVED
- TEST DATA INDICATES THAT VITON RUBBER (UNFILLED FLUOROCARBON) EXHIBITS VERY HIGH EROSION RATES (> 200 MILS/SEC) DEPENDING UPON THE HEAT TRANSFER COEFFICIENT

Chart 72 STS-51C (SRM-15) STS-20 O'RING EROSION SCENARIO

A
- NO EROSION UNTIL SONIC FLOW ESTABLISHED IN FIELD JOINT AREA (0 - 50 PSI)

B
- PRIMARY O'RING SEATING PHASE (50 - 200 PSI)
  - LOW TEMPERATURE SHRINKS O'RING AND INCREASES DUROMETER
  - GAS JET THROUGH PUTTY IMPINGES ON PRIMARY O'RING
  - INITIAL EROSION OF PRIMARY O'RING OCCURS (< 10 MILS)
  - GAS FLOW PAST PRIMARY O'RING OCCURS
    - O'RING PRODUCTS FOUND IN SOOT
    - PUTTY PRODUCTS FOUND IN SOOT
  - GAS FLOW DEPOSITS SOOT AND LOSES HEAT (ΔT = 5265°F) IN CIRCUMFERENTIAL EXPANSION BETWEEN O'RINGS, ΔT = 570°F BETWEEN O'RINGS
  - NO DAMAGE TO SECONDARY O'RING
- BLOW-BY PRIMARY O'RINGS OBSERVED MANY TIMES DURING LOW PRESSURE LEAK CHECKS CONDUCTED BETWEEN 50-200 PSI

Chart 73

HPM Predicted Pressure During Ignition

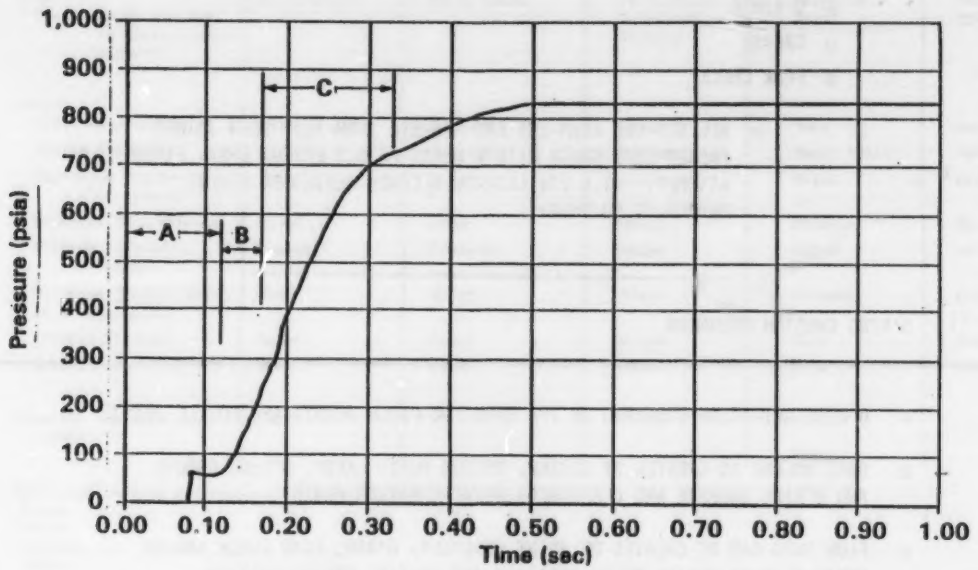


Chart 74

STS-51C (SRM-15) STS-20 O-RING EROSION SCENARIO (CONT)

C O PRIMARY O-RING SEALS AND CONTINUES TO ERODE

- O PRIMARY O-RING SEATS BY THE TIME PRESSURE REACHES 200 PSI
- O FREE VOLUME INCREASES 10X FROM POINT "A" TO POINT "C" DUE TO MOTOR PRESSURIZATION AND JOINT EXPANSION
- O MAJORITY OF O-RING EROSION OCCURS DURING THIS PHASE UNTIL PRESSURE EQUILIBRATION OCCURS AT APPROXIMATELY 330MS
- O DEPTH OF EROSION IS A FUNCTION OF GAS JET SIZE I.E. SMALLER SIZE HIGHER EROSION
- O A67 (L.H.) GAS PATH 2.2 INCHES NEAR O-RING COMPARED TO 1.0 INCH ON A68 (R.H.) I.E. AREA RATIO = 4.8, EROSION DEPTH RATIO = 3.8, ASSUMING FINAL AREA SAME RATIO AS INITIAL

Chart 75 VOLUMETRIC AND THERMAL ANALYSIS AND TEST RESULTS

	MAXIMUM EXPECTED EROSION	MAXIMUM EROSION EXPERIENCED
FIELD JOINT		
PRIMARY	0.092	0.053
SECONDARY	0.060	NONE*
NOZZLE JOINT		
PRIMARY	0.070	0.051
SECONDARY	0.004	NONE

*HEAT EFFECTS WITH NO DEPTH SEEN ON STS-20B

- TESTS SHOW THAT O-RING MAINTAINS SEAL UNDER 3000 PSI WHEN 0.095 INCH MATERIAL IS REMOVED, A 3:1 SAFETY FACTOR FOR PRESSURE EXTRUSION
- SOOT SEEN BEHIND STS-14A NOZZLE PRIMARY SEAL WAS A RESULT OF MOMENTARY GAS PASSAGE BEFORE THE O-RING SEATED

Chart 76

WHY DO MOST O-RINGS NOT ERODE AND WHY DON'T WE SEE SOOT BEHIND PRIMARY O-RINGS MORE OFTEN?

- NO O-RING EROSION OCCURS IF GAS JET IS NOT PRESENT
- IF NO GAS JETS ARE PRESENT, O-RING IS ENERGIZED BY PUTTY COMPRESSING SMALL VOLUME OF AIR TRAPPED BETWEEN PUTTY AND O-RING
  - IF BLOW BY OCCURS DURING SEATING, NO SOOT IS PRESENT IN TRAPPED AIR
- SOOT COMES FROM EROSION OF PUTTY AND/OR O-RING
- NO EVIDENCE THAT PRIMARY O-RING IS LEAKING AFTER INITIAL SEATING PHASE

Chart 77

RATIONALE FOR ACCEPTANCE

- O-RING EROSION ON STS-51C WAS WITHIN EXPERIENCE DATA BASE
- MOMENTARY GAS PASSAGE BY THE PRIMARY SEAL WAS SEEN ON THE STS-14A NOZZLE JOINT
- SECONDARY SEAL HEAT EFFECTS WERE WELL BELOW ANALYTICAL WORST CASE PREDICTIONS
- GAS JET PENETRATES THE PRIMARY SEAL PRIOR TO ACTUATION AND SEALING
- TESTS SHOW THAT O-RINGS WILL SEAL AT 3000 PSI WITH 0.095 INCH OF MISSING MATERIAL (WHICH IS GREATER THAN THE WORST CASE PREDICTION AND ALMOST TWICE THE THE EROSION SEEN ON ANY SRM MOTORS).
- PRIMARY O-RING EROSION OBSERVED TO DATE IS ACCEPTABLE AND WILL ALWAYS BE MORE THAN EROSION ON SECONDARY O-RING IF IT OCCURS.
  - PRIMARY O-RING LEAK CHECK PUSHES O-RING IN WRONG DIRECTION -- SECONDARY O-RING IS SEATED BY LEAK CHECK
  - GAS VOLUME IN FRONT OF PRIMARY O-RING IS 50% GREATER THAN FREE VOLUME BETWEEN O-RINGS
  - GAS WILL COOL AS IT PASSES PRIMARY O-RING AND DIFFUSES CIRCUMFERENTIALLY
- SECONDARY O-RING IS A REDUNDANT SEAL USING ACTUAL HARDWARE DIMENSIONS

Chart 78

FLIGHT READINESS ASSESSMENT FOR STS-51E

- EVALUATION SUMMARY
  - STS-51C PRIMARY O'RING EROSION ON TWO FIELD JOINTS
  - STS-51C SOOT BETWEEN PRIMARY AND SECONDARY O'RINGS ON BOTH FIELD JOINTS - FIRST TIME OBSERVED ON FIELD JOINT
  - EVIDENCE OF HEAT AFFECT ON SECONDARY O'RING OF A68 (RIGHT HAND) CENTER FIELD JOINT BUT NO EROSION - FIRST TIME HEAT AFFECT ON SECONDARY O'RING HAS BEEN OBSERVED
- CONCLUSION
  - STS-51C CONSISTENT WITH EROSION DATA BASE
    - LOW TEMPERATURE ENHANCED PROBABILITY - STS-51C EXPERIENCED WORST CASE TEMPERATURE CHANGE IN FLORIDA HISTORY
    - EROSION IN TWO JOINTS OBSERVED BEFORE - STS-11 AND 14
  - STS-51E COULD EXHIBIT SAME BEHAVIOR
  - CONDITION IS ACCEPTABLE
- STS-51E FIELD JOINTS ARE ACCEPTABLE FOR FLIGHT

Marshall Center Board (February 14, 1985)

Chart 79

PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION	SPECIAL TOPIC
• DM–7 FWC HAS A DELAMINATION IN THE INTERNAL INSULATION WHICH COULD BE THE RESULT OF A GENERIC PROCESS PROBLEM COMMON TO STEEL CASES	MISSION SAFETY	• FWC UNIQUE • STEEL CASE INSULATION HAS BEEN VERIFIED TOLERANT TO INSULATION DELAMINATIONS	YES
• EVIDENCE OF HOT GAS PAST PRIMARY O–RINGS ON 2 CASE JOINTS (PREVIOUSLY OBSERVED ON NOZZLE JOINT)	MISSION SAFETY	ACCEPTABLE RISK BECAUSE OF LIMITED EXPOSURE AND REDUNDANCY (REF. STS 41–C FRR)	NO
• BREAKUP OF –403 AND –404 RINGS IN LEFT HAND SRM EFFECT ON ABILITY TO EVALUATE NOZZLE EROSION	MISSION SAFETY	RECONSTRUCTION ALLOWED VERIFICATION OF EROSION	NO
• APU CONTROLLER CAPACITOR FAILURES ON ORBITER APU	MISSION SAFETY	• ISOLATED TO ONE VENDOR/DATE CODE • PARTS FROM THAT VENDOR/DATE CODE IN IEA SN19 ON STS 51–E • IEA SN19 REPLACED WITH SN11 WHICH HAS PARTS FROM DIFFERENT VENDOR	NO

Level I (February 21, 1985)

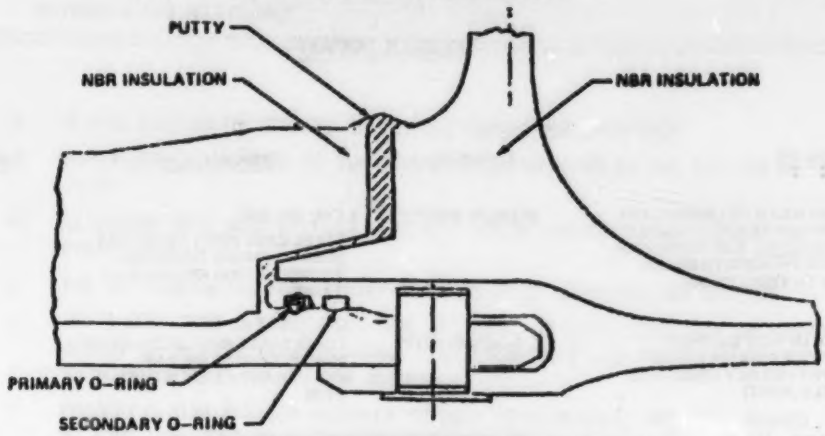
Chart 80

PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION
O EVIDENCE OF HOT GAS PAST PRIMARY O-RINGS ON 2 CASE JOINTS (PREVIOUSLY OBSERVED ON NOZZLE JOINT)	MISSION SAFETY	ACCEPTABLE RISK BECAUSE OF LIMITED EXPOSURE AND AND REDUNDANCY (REF STS 41-C FRR)

Chart 81

SRM–HPM FIELD JOINT



Transcript

Mr. Mulloy: . . . Bring up charts SRB 3 and 3A, we'll discuss an observation that we did have on this flight that we predicted could occur after we saw the erosion on the case joint O-rings on STS-11. You will recall, we have seen some erosion to what is called the primary O-ring, which is the O-ring on the left of the picture there, if you get a path through the putty that allows the hot gas jet to impinge on the primary O-ring. What we observed on 51-C was that we had soot deposited between the primary and the secondary O-ring on two of the case joints, one on each booster. This occurred because we did have a path through the putty that allowed the hot jet to impinge on the primary O-ring and what happens is when we run the leak check on this joint, it pressurizes that primary O-ring in the wrong direction which puts it out of the seat in the O-ring groove for a position to seal against motor pressure. So for about 330 milliseconds there, you are impinging the hot gas while that primary O-ring is seating, and if you do have a path through the putty, you are depositing the products of the O-ring erosion between the primary and the secondary O-ring. The rationale that was developed after observing this erosion on STS-11 was that it was a limited duration that was self-limiting in that as soon as the pressure in the cavity either between the putty and the primary O-ring after the primary O-ring seats, or the pressure between the primary and the secondary O-ring equals the motor pressure, the flow stops and the erosion stops. The maximum erosion that we have seen previously is 53 thousandths – that was back on STS-2. The erosion that we saw on 51-C was 10 thousandths on one O-ring and 38 thousandths on the other, so we believe that because of the limited exposure and the fact that the leak check assures that the secondary O-ring is properly sealing against motor pressure and the fact that the duration is limited, and that we can take 95 thousandths erosion on a primary O-ring and seal against 3,000 psi which is three times the motor pressure, that this represents an acceptable risk.

Go to Chart SRB-4. . . .

STS 51-B FLIGHT READINESS REVIEWS: Charts 82-84

SRB Board (April 8, 1985)

Chart 82

SRM-15 (STS 51-C) DISASSEMBLY UPDATE

- DISASSEMBLY INCOMPLETE AT PREVIOUS FRR
- NOZZLE DISASSEMBLY FROM CASE REVEALED GAS PATHS TO O-RINGS
  - SRM 15-A AT 108°
  - SRM 15-B AT 83°
  - SOOT VISIBLE IN PRIMARY O-RING GROOVE AND LAND

    NO SOOT VISIBLE ON SECONDARY O-RING OR GROOVE
- NO O-RING DAMAGE OR EROSION INCURRED

CONCLUSION: OBSERVATION WITHIN DATA BASE O-RING SEATS AT 50 – 200 psi ACCEPTABLE FOR FLIGHT

Chart 83

NOZZLE ASSEMBLY

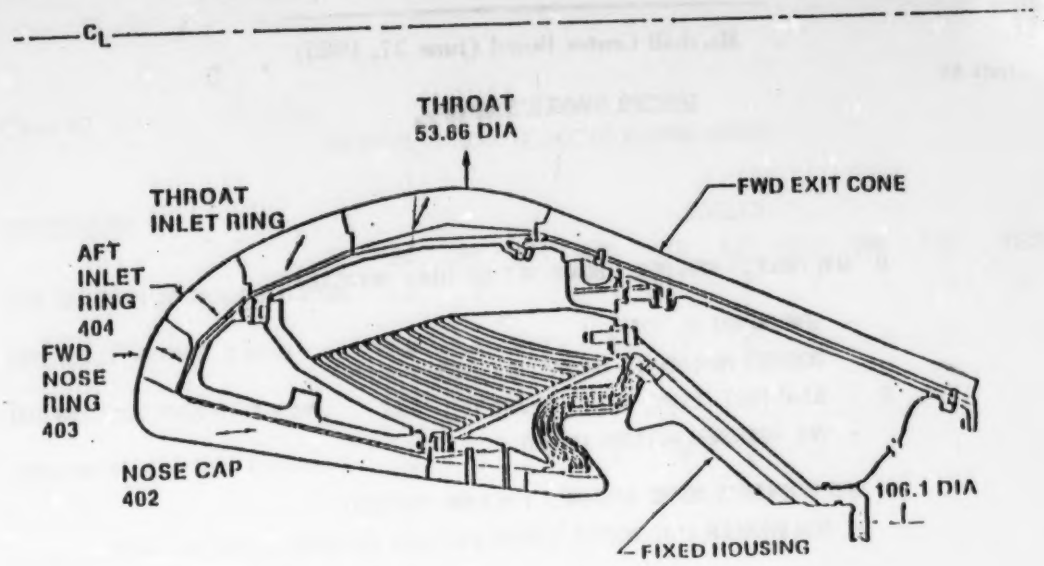


Chart 84

HISTORY OF O-RING DAMAGE

	Cross-Sectional View			Top View	
	Erosion Depth (in.)	Perimeter Affected (deg)	Nominal Diameter (in.)	Length of Maximum Erosion (in.)	Total Heat Affected Length (in.)
STS-20A Fwd Field[AA]	0.010	154.0	0.280	4.25	5.25
STS-20B Con Field (Prim)[AAA]	0.038	120.0	0.280	12.50	58.75
STS-20B Con Field (Sec)[AAA]	None	45.0	0.280	None	29.50
STS-14B Fwd Field	0.028	110.0	0.280	3.00	None
STS-13A Aft Field[A]	None	None	0.280	None	None
STS-11A Fwd Field	0.040	217.0	0.280	3.00	14.50
STS-2B Aft Field	0.033	116.0	0.280	--	--
STS-20A Nozzle[AA]	None	None	0.275	None	None
STS-20B Nozzle[AA]	None	None	0.275	None	None
STS-14A Nozzle[AA]	0.046	171.0	0.275	4.00	7.00
STS-13B Nozzle	0.034	136.0	0.275	1.80	5.60
STS-11B Nozzle	0.039	103.5	0.275	0.75	43.00
QM-4 Nozzle	0.051	101.0	0.275	5.00	11.00
STS-6A Nozzle[A]	None	None	0.275	None	None
STS-6B Nozzle[A]	None	None	0.275	None	None

[A]Hot gas path detected in putty. Indication of heat on O-ring, but no damage
[AA]Soot behind primary O-ring
[AAA]Soot behind primary O-ring, heat affected secondary O-ring

Marshall Center Board (June 27, 1985)

Chart 85

SRB/SPO MANAGER'S BOARDS

- o SRB PROJECT MANAGER'S BOARD MET ON THREE OCCASSIONS
  - SRM ON MAY 8, 1985
  - BOOSTER ASSEMBLIES ON MAY 13, 1985
  - 51-G POST FLIGHT DELTA ON JUNE 21, 1985
  - ALL ASSIGNED ACTIONS CLOSED
- o SPO MANAGER'S BOARD ASSIGNED 1 ACTION (CLOSED)
  - NEW PROBLEM (51B NOZZLE O-RING EROSION) REPORTED AFTER SPO BOARD

Chart 86

PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION
UNUSUAL EROSION OBSERVED ON PRIMARY AND SECONDARY O-RINGS OF SRM 16A NOZZLE TO CASE JOINT (STS 51-B) -PRIMARY O-RING APPARENTLY NEVER SEATED -SECONDARY O-RING HAD MINOR EROSION	FLIGHT SAFETY	-EVIDENCE OF HOT GAS PAST PRIMARY NOT UNPRECEDENTED SINCE LEAK CHECK SEATS PRIMARY O-RING UPSTREAM IN GROOVE -LEAK CHECK ASSURES GOOD SECONDARY SEAL -DURATION OF HOT GAS FLOW PAST PRIMARY SEAL IS LIMITED BY TIME REQUIRED TO FILL VOLUME BETWEEN PRIMARY AND SECONDARY SEALS -LIMITED DURATION OF FLOW LIMITS EROSION ON SECONDARY SEAL TO TEST VERIFIED ACCEPTABLE LEVELS

Chart 87

PREVIOUS HISTORY OF NOZZLE O-RING DAMAGE

OBSERVATION	NOZZLES									
	-6	QM4	4.1B	4.1C	4.1D	5.1C	5.1D	QM2	5.1B	TOTAL
HOT GAS PATH TO PRIMARY O-RING	2	1	1	1	1	2	2	1	2	13
EROSION OF PRIMARY O-RING	0	1	1	1	1	0	2	1	2	9
HOT GAS PAST PRIMARY O-RING	0	0	0	0	1	2	0	0	1	4
EROSION OF SECONDARY O-RING	0	0	0	0	0	0	0	0	1	1

Chart 88

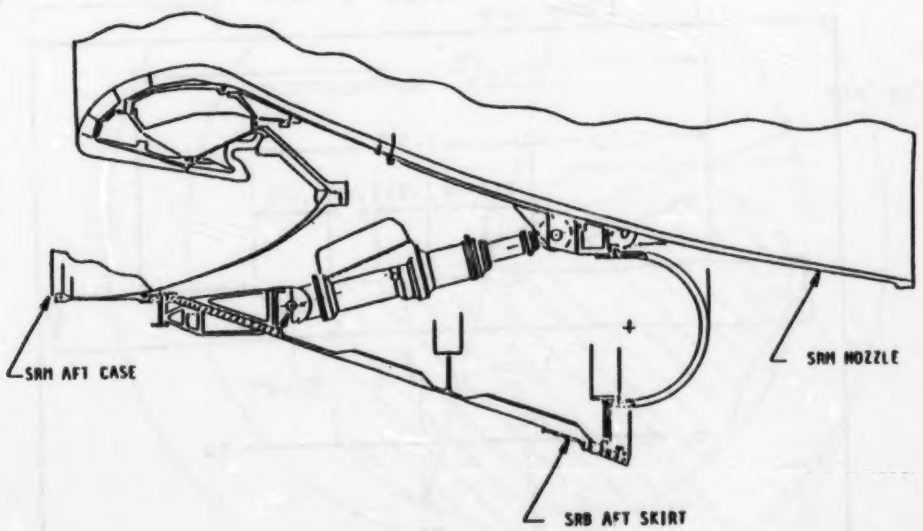
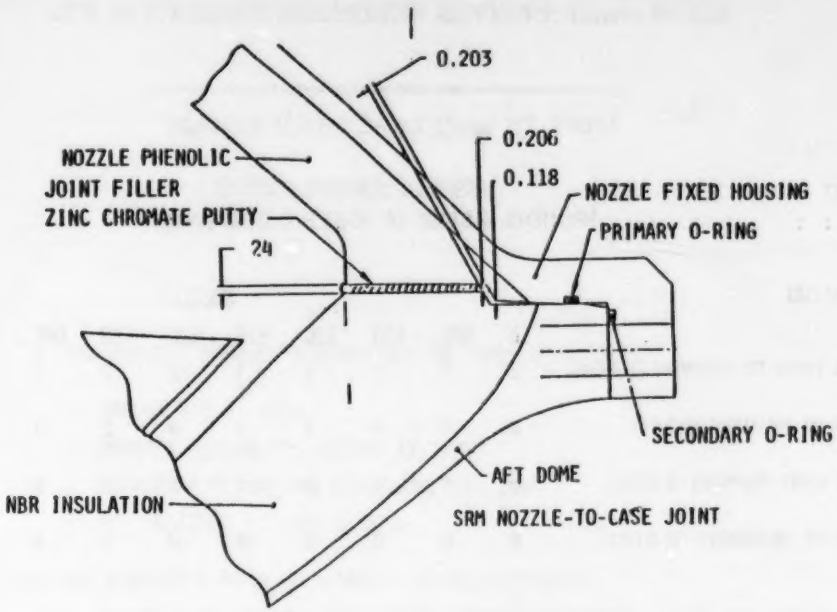


Chart 89



SRM NOZZLE TO CASE JOINT

Chart 90

DRAWING/CALCULATION SHEET

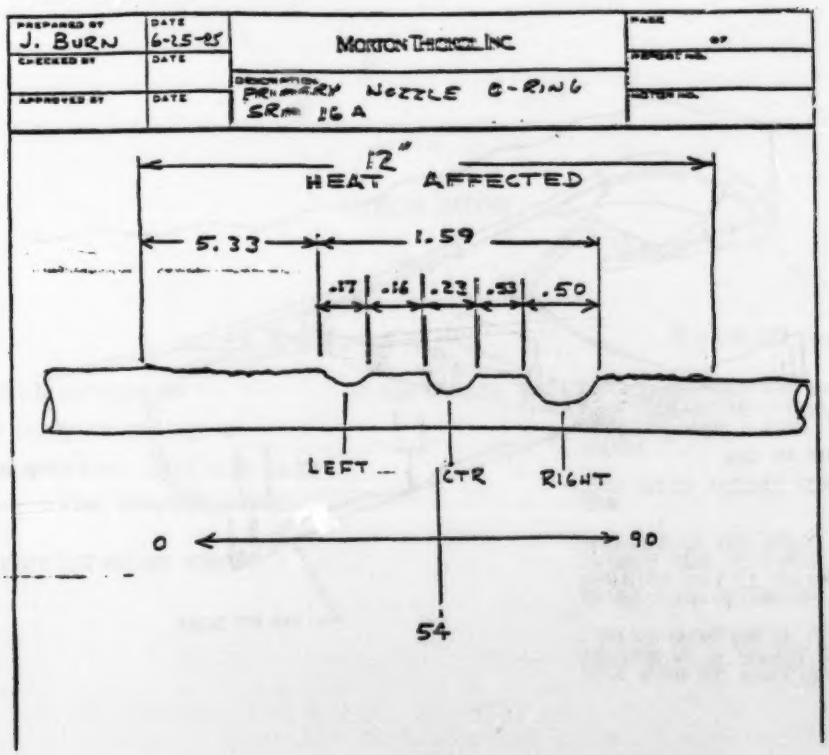


Chart 91

SRM 16A
PRIMARY NOZZLE
O-RING
RIGHT NOTCH TOWARDS 90°
54° LOCATION
LOOKING TOWARDS 90°

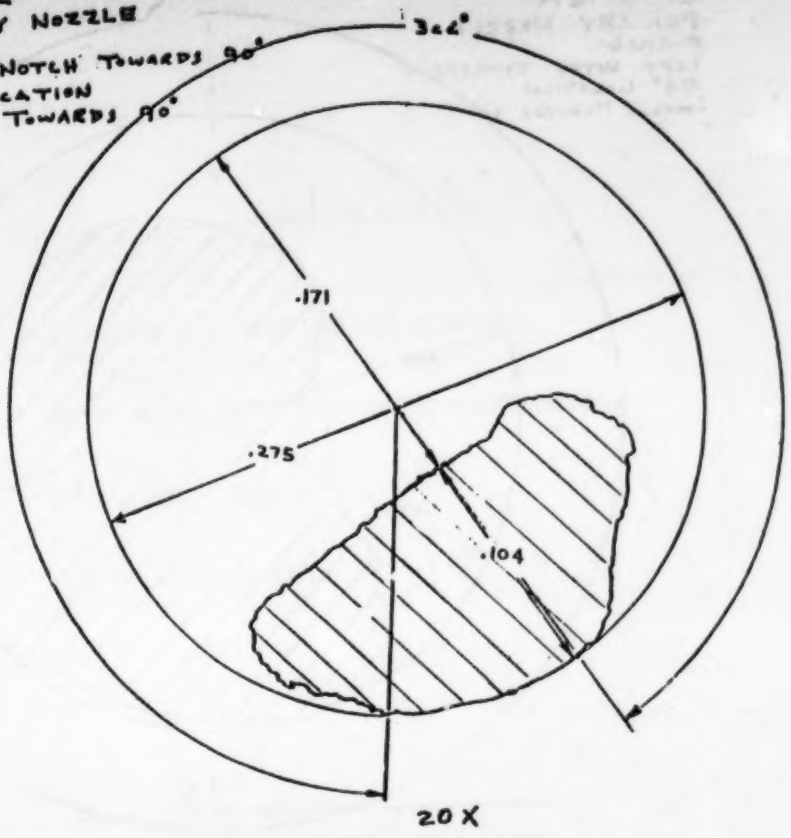


Chart 92

SRM 16A
PRIMARY NOZZLE
O-RING
CTR NOTCH
54° LOCATION
LOOKING TOWARDS 90°

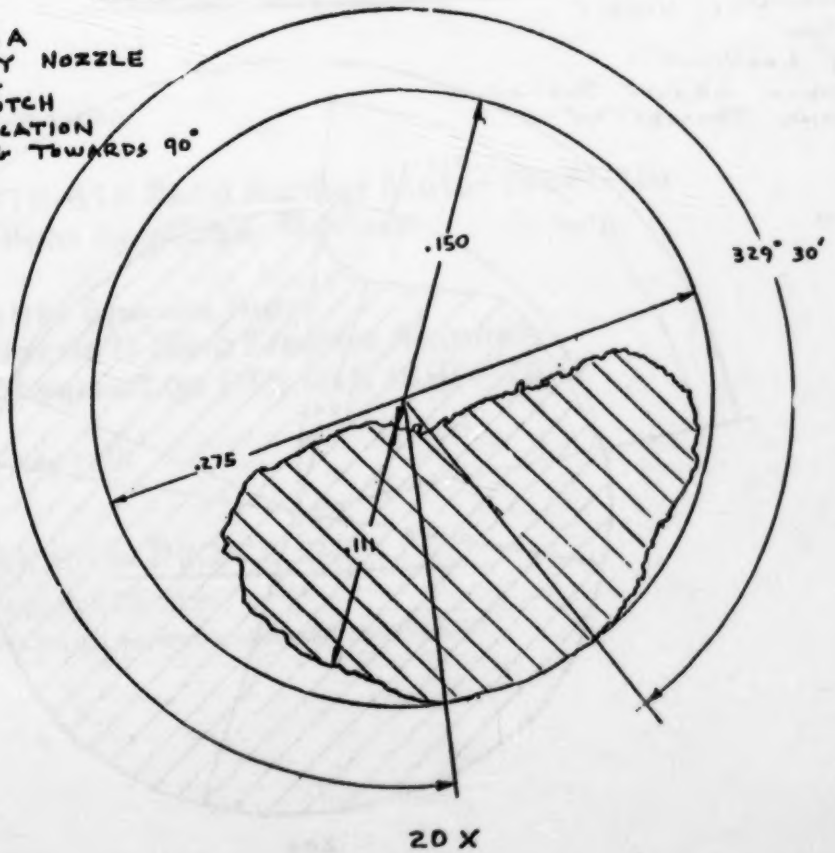


Chart 93

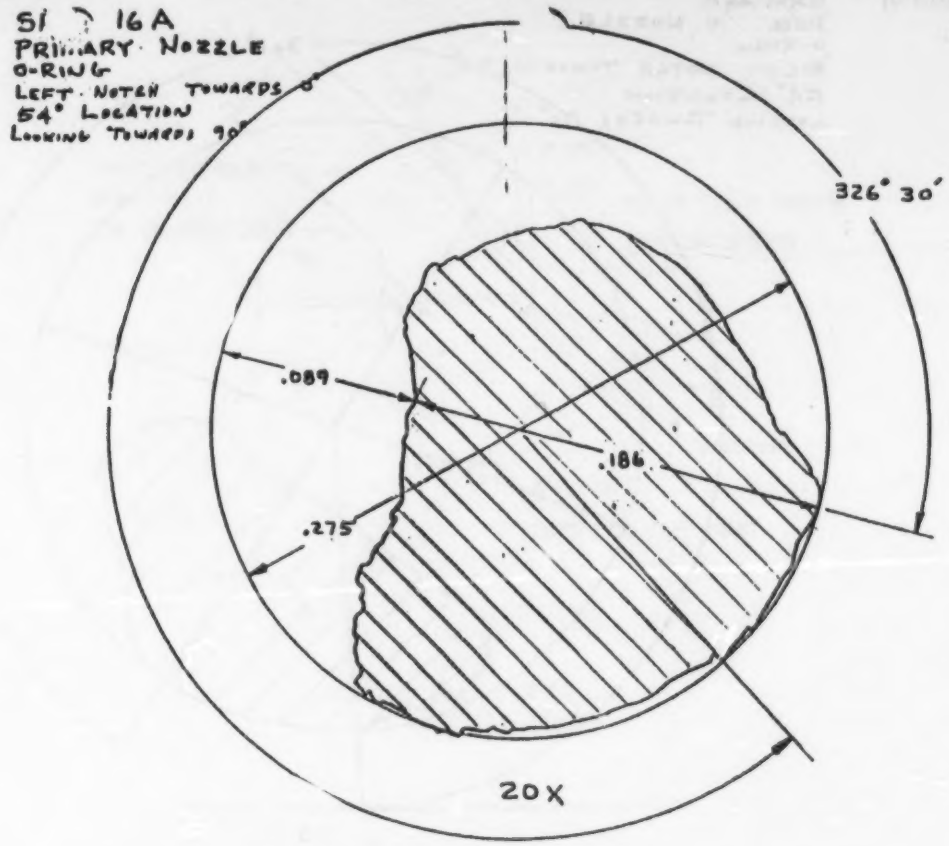


Chart 94

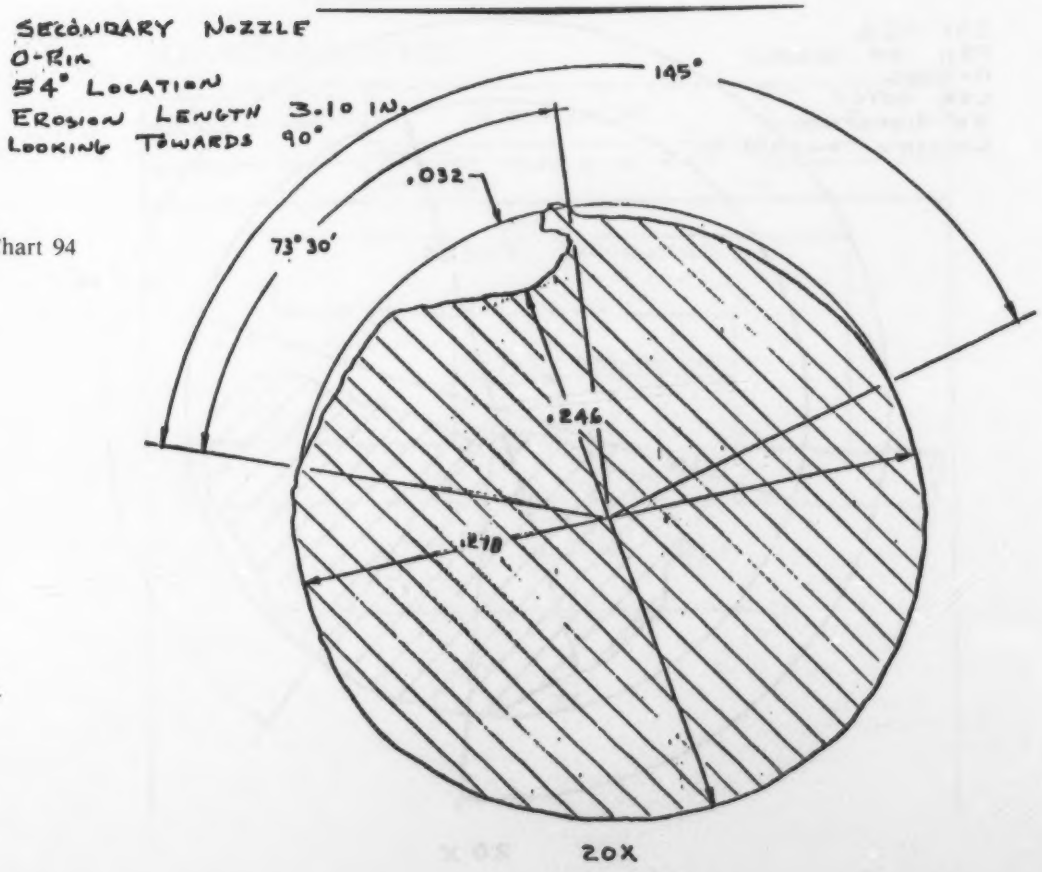


Chart 95

RESOLUTION ACTIVITIES

- DEFINE LEAK TEST PARAMETERS USED ON SRM-16A
- DEFINE INITIAL CONDITION TO PRODUCE OBSERVED RESULTS
- DEFINE LIMITING CONDITION
- VERIFY LIMITING CAPABILITY

Combined Marshall Boards (July 1, 1985)

Chart 96

TWR-15088

STS-51F Solid Rocket Motor (SRM-19) Flight Readiness Review

SRM Special Topic
Nozzle O-Ring Erosion Anomaly Observed on STS-51B (SRM-16A)

1 July 1985

MORTON THIOKOL, INC.
Wasatch Division
P.O. Box 524, Brigham City, Utah 84302 (801) 863-3511

Chart 97

AGENDA

- SECTION A--PROBLEM DESCRIPTION
- SECTION B--COMPARISON WITH PAST HISTORY
- SECTION C--STS-51B NOZZLE JOINT EROSION SCENARIO
- SECTION D--COMPARISON OF AS-BUILT 51-B NOZZLE JOINTS WITH 51-F
- SECTION E--FLIGHT READINESS ASSESSMENT FOR STS-51F

Chart 98

Problem Description (Chart A-1)

SRM Nozzle-to-Case Joint

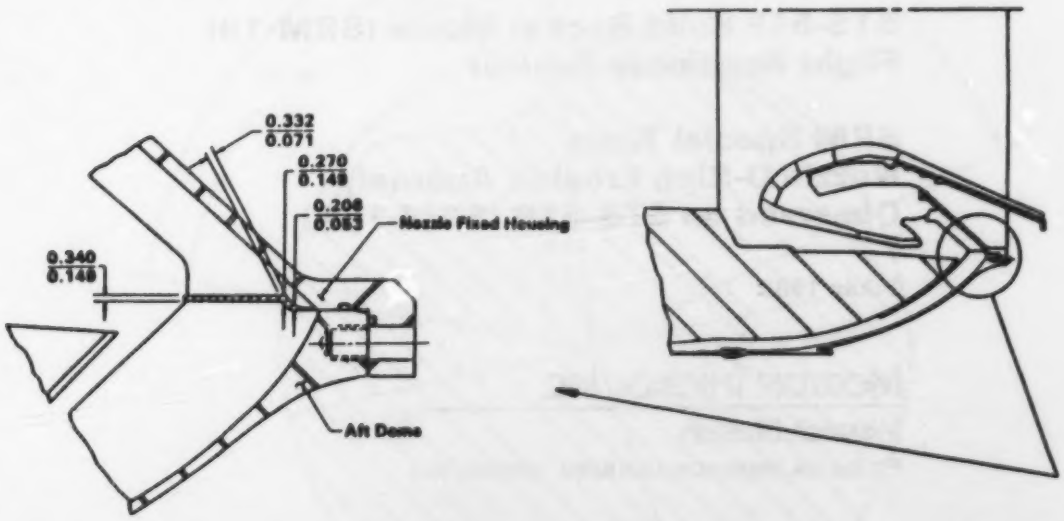


Chart 99

POST FIRED HARDWARE EVALUATION (CHART A-2)

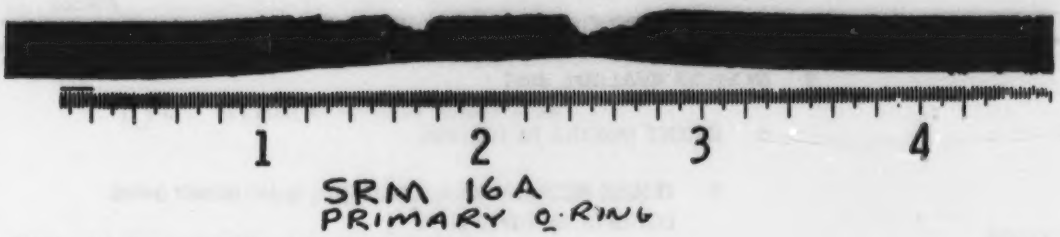
- ON SHI 16A NOZZLE/DOME JOINT
  - EVIDENCE INDICATES THE FOLLOWING
    - AT MOTOR PRESSURIZATION A HOT GAS PATH TO THE PRIMARY O-RING EXISTED OR WAS FORMED AT 54°
      - PHOTO 85641-35
      - PHOTO 85641-1
      - PHOTO 85646-14
    - EXTENSIVE PRIMARY O-RING AND DOME NBR EROSION OCCURRED AT HOT GAS PATH
    - SURFACES BETWEEN O-RINGS HEAVILY SOOTED ABOUT 180° LIGHTLY SOOTED OVER REMAINDER
      - EROSION THROUGH O-RING AT BLOW-BY WAS 1.59 INCHES WIDE (PHOTO 85642-6)
    - HEAT AFFECTED ZONE WAS 12 INCHES

Chart 100

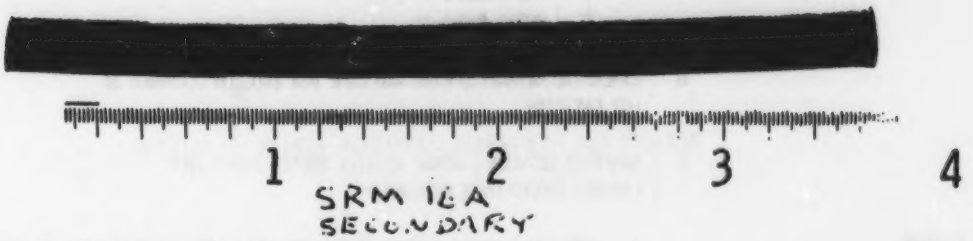
4 Photographs - Not Reproducible

Chart 101

Problem Description (Chart A-7)



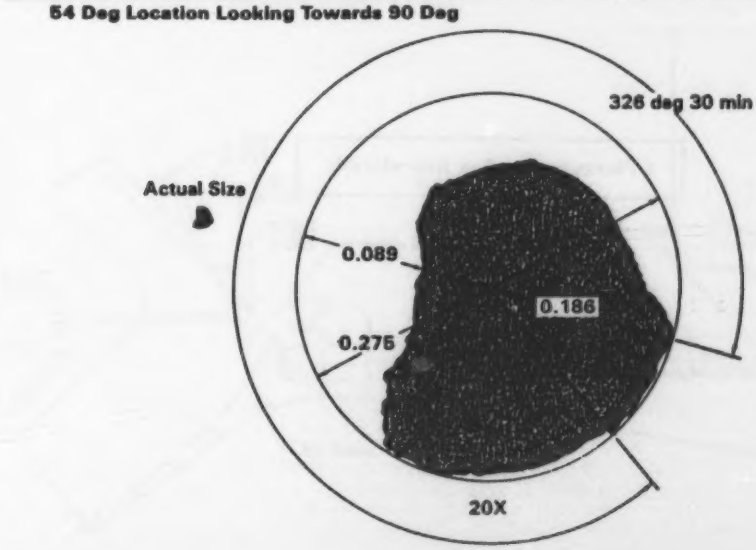
SRM-16A Primary O-Ring Nozzle Erosion 88842-8



SRM-16A Secondary O-Ring Nozzle Erosion 88842-2

Chart 102

SRM-16A Primary Nozzle O-Ring—Left Notch (Chart A-8)



SRM-16A Primary Nozzle O-Ring—Left Notch (Chart A-9)

Chart 103

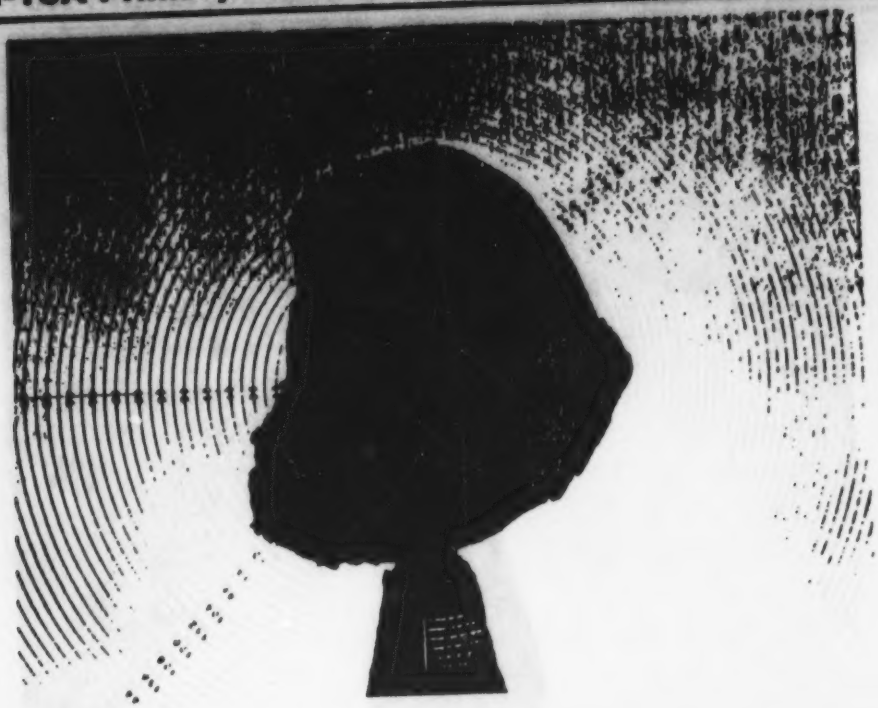
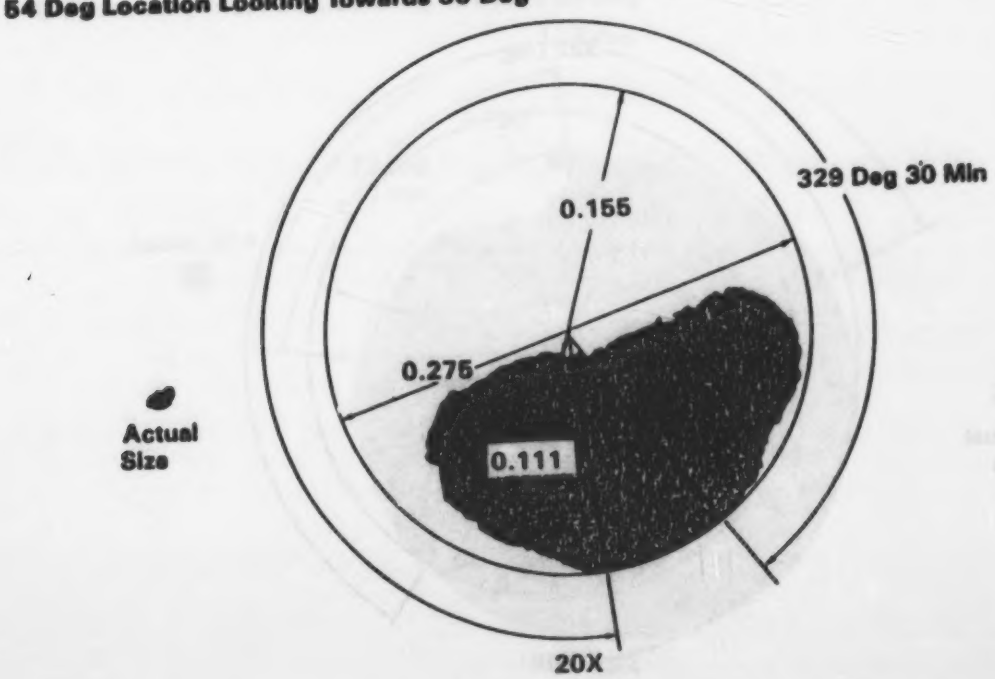


Chart 104

SRM-16A Primary Nozzle O-Ring--Center Notch (Chart A-10)



SRM-16A Primary Nozzle O-Ring—Center Notch (Chart A-11)

Chart 105

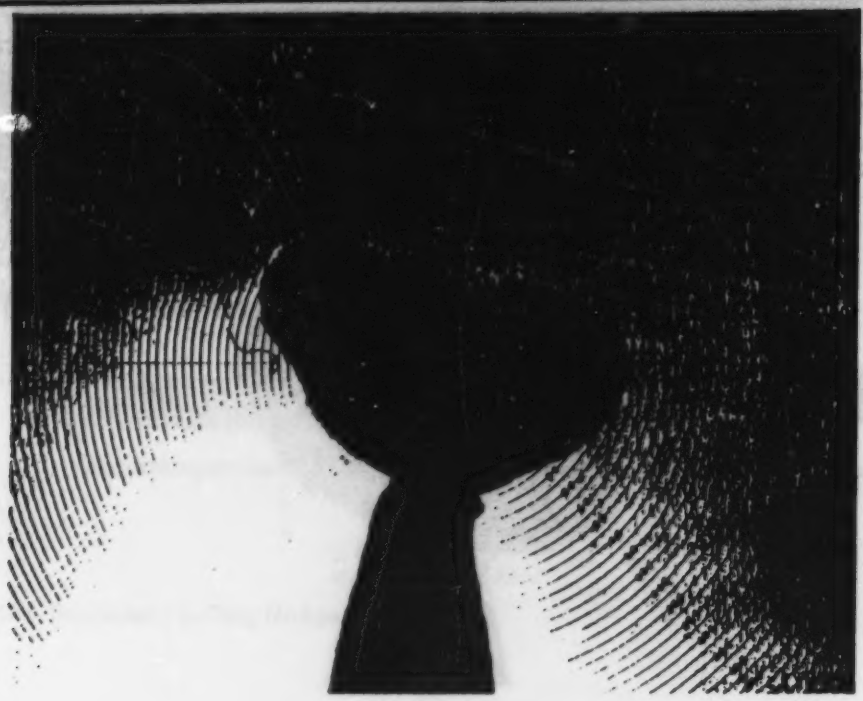
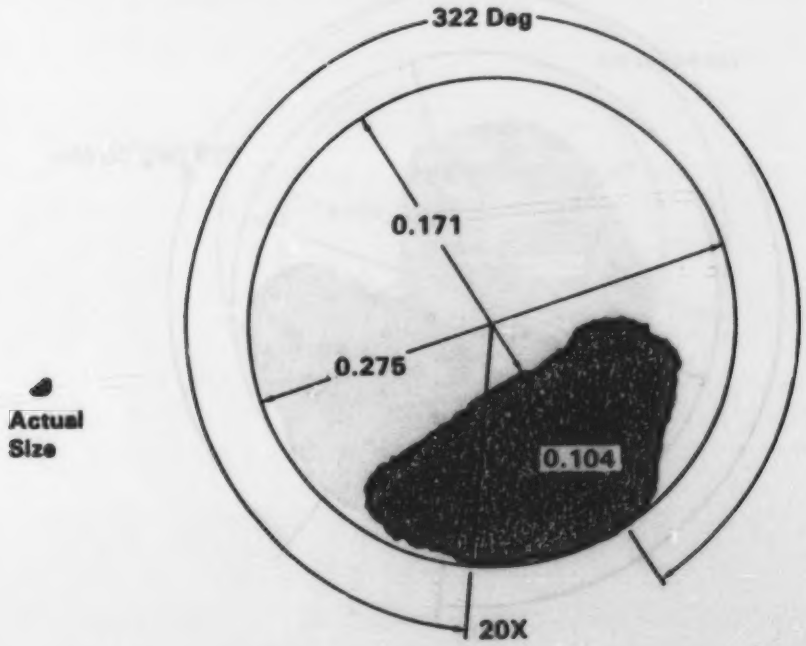


Chart 106

SRM-16A Primary Nozzle O-Ring—Right Notch (Chart A-12)

54 Deg Location Looking Towards 90 Deg

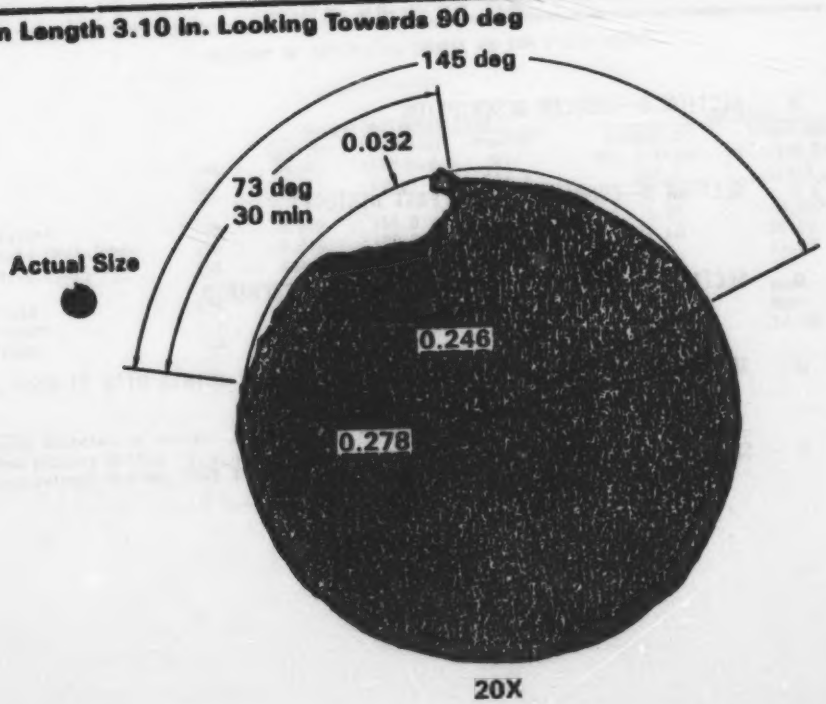


SRM-16A Primary Nozzle O-Ring–Right Notch (Chart A-13)

Chart 107

Chart 108

S A-16A Secondary Nozzle Ring—54 Deg Location (Chart A-14)



SRM-16A Secondary Nozzle O-Ring (Chart A-15)

Chart 109

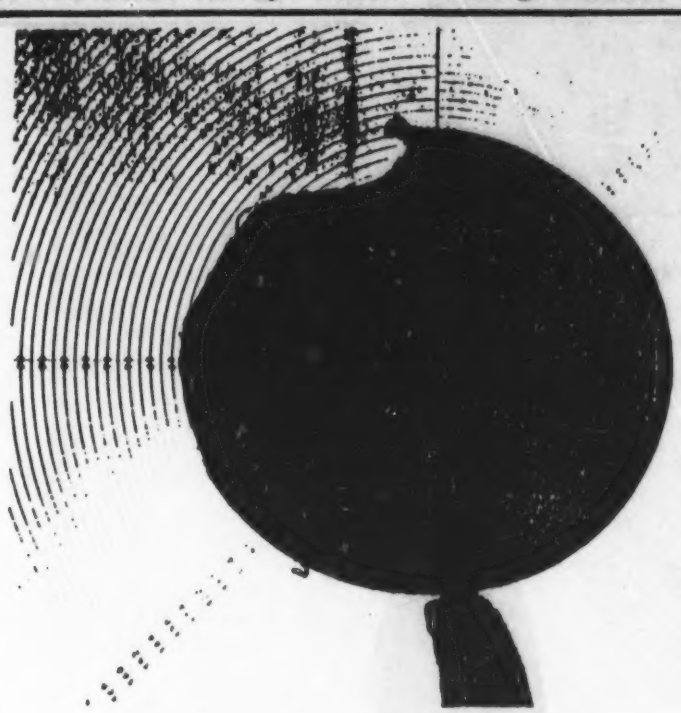


Chart 110

AGENDA

- SECTION A--PROBLEM DESCRIPTION
- SECTION B--COMPARISON WITH PAST HISTORY
- SECTION C--STS-51B NOZZLE JOINT EROSION SCENARIO
- SECTION D--COMPARISON OF AS-BUILT 51-B NOZZLE JOINTS WITH 51-F
- SECTION E--FLIGHT READINESS ASSESSMENT FOR STS-51F

Chart 111

COMPARISON WITH HISTORY (CHART B-1)

HISTORY OF SRM O-RING DAMAGE ON SRM NOZZLES

	SRM No.	Cross-Sectional View: Erosion Depth (in.)	Cross-Sectional View: Perimeter Affected (Deg)	Cross-Sectional View: Nominal Dia (in.)	Top View: Length of Max Erosion (in.)	Top View: Total Heat Affected Length (in.)	Clocking Location (Deg)
LH Nozzle **	18A	0.013	62.0	0.275	1.12		151.2
RH Nozzle **	18B	0.023	226.0	0.275	0.88		270, 342
51B LH Nozzle (Prim)***	16A	0.171	322.0	0.275	1.59	12.0	54.0
51B LH Nozzle (Sec)***	16A	0.032	145.0	0.275	3.1	3.1	54.0
51B RH Nozzle	16B	0.005	124.0	0.275	3.4	4.7	14.4
DM-7 Nozzle	DM-7	0.088	246.5	0.275	12.0	34.0	46.8
51D LH Nozzle	17A	0.011	63.0	0.275	2.12	5.65	14.4
51D RH Nozzle	17B	0.068	126.0	0.275	6.0	11.0	116
51C LH Nozzle **	15A	None	None	0.275	None	None	109
51C RH Nozzle **	15B	None	None	0.275	None	None	63
41D LH Nozzle **	13A	0.046	121.0	0.275	4.00	7.00	309.6
41C RH Nozzle	11B	0.034	136.0	0.275	1.80	5.60	
RH Nozzle	10B	0.039	103.5	0.275	0.75	45.00	
-4 Nozzle	QM-4	0.051	101.0	0.275	5.00	11.00	
STS-6 LH Nozzle*	6A	None	None	0.275	None	None	
STS-6 RH Nozzle*	6B	None	None	0.275	None	None	

*Hot gas path detected in putty. Indication of heat on O-ring, but no damage
**Soot behind primary O-ring
***Soot behind primary O-ring, heat affected secondary O-Ring

.272 - 3 - 86

Chart 112

COMPARISON WITH HISTORY (CHART B-2)

HISTORY OF SRM O-RING DAMAGE ON SRM FIELD JOINTS

	SRM No.	Cross-Sectional View: Erosion Depth (in.)	Cross-Sectional View: Perimeter Affected (deg)	Cross-Sectional View: Nominal Dia (in.)	Top View: Length of Max Erosion (in.)	Top View: Total Heat Affected Length (in.)	Clocking Location (deg)
51C LH Fwd Field**	15A	0.010	154.0	0.280	4.25	5.25	163
51C RH Ctr Field (Prim)***	15B	0.038	120.0	0.280	12.50	58.75	354
51C RH Ctr Field (Sec)***	15B	None	45.0	0.280	None	29.50	354
41D RH Fwd Field	13B	0.028	110.0	0.280	3.00	None	275
41C LH Aft Field*	11A	None	None	0.280	None	None	
41B LH Fwd Field	10A	0.040	217.0	0.280	3.00	14.50	351
STS-2 RH Aft Field	2B	0.053	116.0	0.280	--	--	90

*Hot gas path detected in putty. Indication of heat on O-ring, but no damage
**Soot behind primary O-ring
***Soot behind primary O-ring, heat affected secondary O-ring

Chart113

Past History Comparison (Chart B-3)

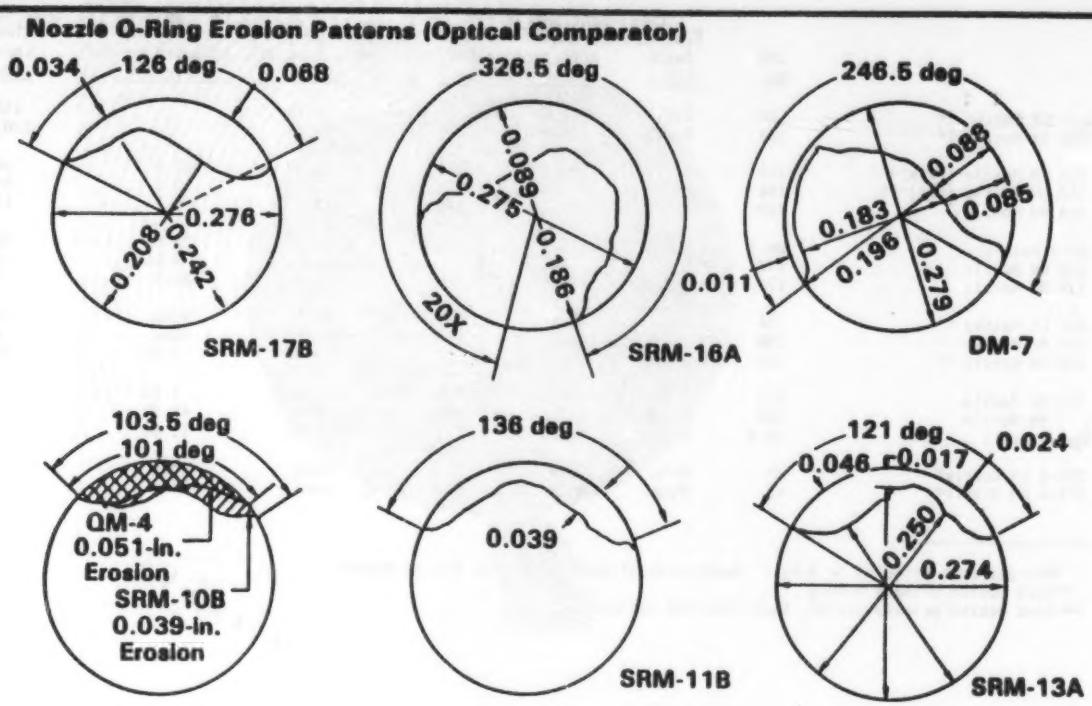
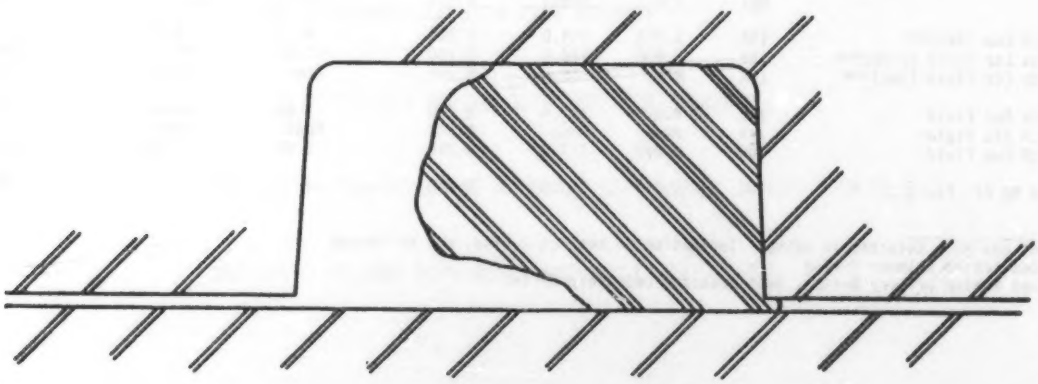


Chart 114

Nozzle Joint, Estimated Pressurized Configuration—Primary O-Ring Seal (Chart B-4)



Scale: 10X Size

Chart 115

AGENDA

- SECTION A--PROBLEM DESCRIPTION
- SECTION B--COMPARISON WITH PAST HISTORY
- SECTION C--STS-51B NOZZLE JOINT EROSION SCENARIO
- SECTION D--COMPARISON OF AS-BUILT 51-B NOZZLE JOINTS WITH 51-F
- SECTION E--FLIGHT READINESS ASSESSMENT FOR STS-51F

Chart 116

STS-51B NOZZLE JOINT EROSION SCENARIO (CHART C-1)

- POSITIVE LEAK CHECK AT 100 PSIG CONFIRMS SECONDARY O-RING SEAL
- VACUUM PUTTY MASKED LEAK CHECK ON UPSTREAM SIDE AT 100 PSIG
- PRIMARY O-RING IS LOCATED IN FORWARD PORTION OF O-RING GROOVE AS A RESULT OF LEAK CHECK - SECONDARY O-RING IS IN PROPER LOCATION
- GAS PATHS THROUGH PUTTY FORMED DURING NOZZLE ASSEMBLY OR PARTIAL GAS PATH FORMED AS A RESULT OF BLOW-BY THE O-RING DURING LEAK CHECK
- AT SRM IGNITION GAS JET FOLLOWS PATHS THROUGH PUTTY AND IMPINGES ON PRIMARY O-RING
- PRIMARY O-RING DOES NOT COMPLETELY SEAL AT 54° AND PART OF GAS JET CONTINUES PAST PRIMARY SEAL TO SECONDARY O-RING
- SECONDARY O-RING IS FACE SEAL AROUND CORNER--GAS JET DISPERSES WITH APPROXIMATELY 1/4 OF MASS FLUX OF JET IMPINGING ON SECONDARY SEAL
- SECONDARY O-RING SEATS AND SEALS JOINT
- EROSION STOPS WHEN IGNITION TRANSIENT IS COMPLETED AND MOTOR REACHES EQUILIBRIUM PRESSURE; I.E., APPROXIMATELY 600 MSEC

Chart 117

VACUUM PUTTY SUBSCALE TESTING SUMMARY (REF. TWR-1384) (CHART C-2)

PUTTY TYPE	GAP (IN)	PRESSURE (PSI)	TEMP. (°F)	PUTTY THICKNESS END OF CLEVIS (IN)	TIME BLOW-THRU MIN:SEC
FULLER O'BRIEN	0.010	50	R.T.	0.04	0:10
RANDOLPH INITIAL TYPE II	0.010	50	R.T.	0.04	9:20
RANDOLPH INITIAL TYPE II	0.010	50	R.T.	0.10/0.15	41:54
RANDOLPH INITIAL TYPE II	0.010	75	R.T.	0.10	5:50
RANDOLPH INITIAL TYPE II	0.010	75	R.T.	0.10	9:41
RANDOLPH INITIAL TYPE II	0.010	100	R.T.	0.10	1:56
RANDOLPH INITIAL TYPE II	0.010	154	R.T.	0.10	1:16
RANDOLPH INTERIM TYPE II	0.010	100	40	0.10	4:40
RANDOLPH INTERIM TYPE II	0.010	100	40	0.10	7:21
RANDOLPH INTERIM TYPE II	0.010	100	80	0.10	13:53
RANDOLPH INTERIM TYPE II	0.010	150	78.5	0.10	3:38
RANDOLPH FINAL TYPE II	0.010	100	40	0.10	6:55
RANDOLPH FINAL TYPE II	0.010	100	40	0.10	9:13
RANDOLPH FINAL TYPE II	0.010	100	81.5	0.10	6:55
RANDOLPH FINAL TYPE II	0.010	150	39	0.10	1:34
RANDOLPH FINAL TYPE II	0.010	150	80	0.10	0:41

*NOZZLE GAP IS 0.008 TO 0.016 INCHES

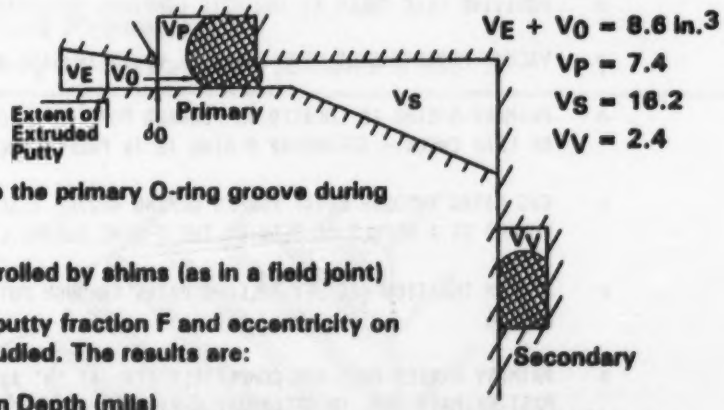
Chart 118

Simulation of Nozzle Joint Primary O-Ring (Chart C-3)

- Model applies equally to nozzle joints and field joints

  However, in a nozzle joint:

  - Putty can extrude up to the primary O-ring groove during assembly
  - Eccentricity is not controlled by shims (as in a field joint)



- Consequently, the effects of putty fraction F and eccentricity on nozzle O-ring erosion were studied. The results are:

F	Erosion Depth (mils) δ_0 = 0.0125	δ_0 = 0.010	δ_0 = 0.005
0.00	53.9		
0.50	47.4		
0.75	44.3	70.8	111.2
0.95	37.8		

- For a field joint O-ring with the same heat loss model, erosion depth was predicted to be 37 mils

Chart 119

Scenarios of Burn-Through (Chart C-4)

- Could high eccentricity with jet-impingement cause erosion this severe?
- Nozzle O-rings have been shown to survive erosion depths of
  - 88 mil in hot motor firing (DM-7); 125 mil in hot subscale tests
  - 155 mil subscale cold pressurization tests
- However, primary O-rings that have eroded more than 145 mil have failed (allowed erosion of secondary O-rings) in hot subscale tests

Scenario No. 1

Jet-Impingement Erosion

Scenario No. 2

Blowby Convective Heating With Jet-Impingement

Feature		
Starts late	Pressurization of secondary cavity	Starts early
950 psi ~ constant	Pressure in primary cavity during	Motor pressure transient
	mass flow rate	
Short	Filling time	Long

Chart 120

BLOW-BY EROSION OF PRIMARY O-RING (CHART C-5)

- THE BLOW-BY FLOW THROUGH THE PRIMARY O-RING IS APPROXIMATED AS PIPE FLOW
- THE DITTUS/BOELTER MODEL OF WALL HEATING IS COMBINED WITH THE VITON EROSION MODEL TO PREDICT THE GROWTH-RATE OF THE RADIUS OF THE BLOW-BY TUNNEL.
- THE RESULTING DEPTH OF BLOW-BY EROSION WAS PREDICTED BY MODEL TO BE 87 MILS USING CALCULATED HISTORY OF BLOW-BY MASS FLOW RATE
- THUS, THE COMBINED EFFECT OF BLOW-BY EROSION (87 MILS) AND JET-IMPINGEMENT EROSION (88 MILS REALISTIC AS ON DM-7) COULD CAUSE A TOTAL EROSION OF 175 MILS.
- IT IS CONCLUDED THAT THE BLOW-BY SCENARIO COULD PRODUCE AS MUCH EROSION AS OBSERVED ON SRM-16A.

Chart 121

Model of Jet-Impingement Erosion of Secondary O-Ring (Chart C-6)

- A triple-tunnel burn-through shoots three jets toward the flange wall with mass flow rate $\dot{M}_1$
- Approximate these jets as a single equivalent jet with width of 0.17 + 0.23 + 0.50 = 0.90 in.
- Assume no jet spreading until impingement on the wall
- Let a fraction R of the incident flow rate be deflected down onto the secondary O-ring (now open to impingement due to joint rotation)
- Worst-case conditions are:
  - No jet spreading
  - 100-percent deflection (R = 1) onto secondary O-ring
  - Small secondary gap δ_2
  - Instantaneous (t = 0) burn-through of primary O-ring
  - Instantaneous replenishment of primary cavity
- Secondary gap was predicted to open at rate of 20 mil/1,000 psi, so a conservative choice of 10 mil/1,000 psi was assumed
- The strongest jet was assumed (height δ_1 (mil) = 12 + 15P/1,000)
- The effect of primary/secondary chamber coupling was shown to cause reduced secondary erosion, so uncoupled (worst) case was used

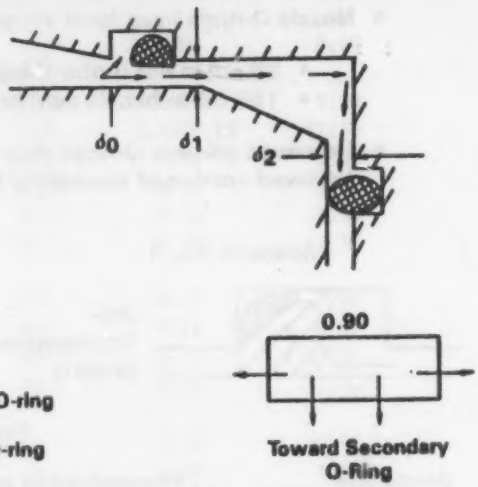


Chart 122

SECONDARY O-RING EROSION RESULTS (CHART C-7)

o MODEL PREDICTS THE FOLLOWING EROSION DEPTHS (MILS) FOR THE SECONDARY O-RING:

IMPINGING FLOW FRACTION	SCENARIO #1	SCENARIO #2
1.0	10	75
0.5		51
0.3		37
0.2		23
0.1	5	8

o CONCLUSIONS

- o SCENARIO #1 CANNOT PREDICT ENOUGH SECONDARY O-RING EROSION (32 MILS OBSERVED)
- o SCENARIO #2 PREDICTS THE CORRECT EROSION OF SECONDARY O-RING IF FLOW FRACTION IS ABOUT 1/4
- o WORST PREDICTED EROSION OF SECONDARY O-RING IS 75 MILS IF ALL FLOW IMPINGES ON O-RING

Chart 123

STS-51B NOZZLE JOINT EROSION SCENARIO (CHART C-8)

- SUBSCALE (5 INCH DIAMETER) O-RINGS WERE PRESSURIZED TO 3000 PSIA IN TEST FIXTURE WITH O-RING MATERIAL REMOVED TO DETERMINE WHEN SEAL WOULD FAIL
  - O-RING REMAINED SEALED WITH 0.155 INCHES REMOVED
  - SEAL FAILED WITH 0.160 INCHES REMOVED
- SUBSCALE 5 INCH DIAMETER MOTOR FIRINGS WERE CONDUCTED AT 900 PSIA WITH JET IMPINGEMENT ON THE O-RING
  - PRIMARY O-RINGS REMAINED SEALED WITH EROSION UP TO 0.125 INCHES
  - PRIMARY O-RING FAILED AT 0.145 INCHES EROSION AND 0.161 INCHES EROSION WITH 0.005 INCH AND 0.009 INCH EROSION RESPECTIVELY ON SECONDARY SEAL
- WORST CASE PREDICTED EROSION ON SECONDARY O-RING OF 0.075 INCHES IS WELL BELOW DEMONSTRATED SEALING CAPABILITY OF ERODED O-RING

Chart 124

AGENDA

- SECTION A--PROBLEM DESCRIPTION
- SECTION B--COMPARISON WITH PAST HISTORY
- SECTION C--STS-51B NOZZLE JOINT EROSION SCENARIO
- SECTION D--COMPARISON OF AS-BUILT 51-B NOZZLE JOINTS WITH 51-F
- SECTION E--FLIGHT READINESS ASSESSMENT FOR STS-51F

Chart 125 COMPARISON OF AS BUILT 51-B NOZZLE JOINTS WITH 51F (CHART D-1)

	STS-51B		STS-51F	
CHARACTERISTIC	SRM-16A	SRM-16B	SRM-19A	SRM-19B
Nozzle Installation				
Location	HTI	HTI	HTI	HTI
Mode	Horizontal, 90° Up	Horizontal, 90° Up	Horizontal, 90° Up	Horizontal, 90° Up
Date	30 May 1984	14 June 1984	11 November 1984	17 November 1984
Vacuum Putty				
Type	Randolph Tape	Randolph Tape	Randolph Tape	Randolph Tape
Stock Number	5809 5808	5809 5808	5809 5808	5809 5808
Lot Number	0009 0009	0009 0009	0009, 0011 0010	0011 0010
Material DRs	111334 None	111334 None	111334 None	None None
— — — —	Three batches submitted as one lot, retested and used.	See SRM-16A.	See SRM-16A, no DRs on lot 0011.	
Previously Fired Joints Using Same Putty	Field--16A, 14B, 13B aft, 14A stf, aft, 14B all. Nozzle--(5808) 13A°.	See SRM-16A	5809-0009, See SRM-16A. Others see SRM-19B.	Field--15A°, 13B fwd, 16A. Nozzle--(5809) 10B° (5808) 17B°, 16A°, 18B°.
Layup Configuration	STW7-3193 N/C-1	STW7-3193, N/C-1	STW7-3193 N/C-1,2,3	STW7-3193 N/C-1,2,3
Weight	31.95	30.05	28.64	30.04
Nozzle	17.80	17.71	15.98	15.66
Case	14.15	12.34	12.66	14.38
Layup DRs	113045, Thin putty, 2.7 lbs added to bring putty to proper thickness	113823 Thin putty, 4.2 lbs added to bring putty to proper thickness.	None	None
Leak Check				
Method	STW7-2747 A-2,3,4,5,6,7	STW7-2747 A-2,3,4,5,6,7	STW7-2747 B-8	STW7-2747 B-8
Maximum Pressure	100 psig	100 psig	300 psig	300 psig
DRs	Initial leak check failed, secondary o-ring found cut, parts cleaned and reassembled per planning.	None	None	None

* Joints with host affected or damaged o-rings

Chart 126 COMPARISON OF AS-BUILT 51B NOZZLE JOINTS WITH 51F (CHART D-2)

METAL HARDWARE HISTORY

	STS-51B		STS-51F	
CHARACTERISTICS	SRM-16A	SRM-16B	SRM-19A	SRM-19B
AFT DOME				
1U50129-XX Dash No.	-08	-08	-10*	-08
S/N	028	016	010	029
No. of Refurbishments	0	1	2	0
DRs	47120; 14.4° bolt hole large, helicoil 47116; 0, 133.2, 237.6 bolt holes damaged, helicoil	None	None	None
FIXED HOUSING				
1U50088-05				
S/N	015	026	033	029
No. of Refurbishments	1	0	0	0
DRs	None	None	None	None
O-RING SQUEEZE				
Primary (%, inches)	15.89, .044	16.38, .045	15.51, .042	17.07, .046
Secondary (%, inches)	15.09, .041	16.08, .044	15.09, .041	15.75, .043

*-10 made from -08, cutout in OD leg to accomodate PVC leak test port.

Chart 127

COMPARISON OF AS BUILT 51B NOZZLE JOINTS WITH 51F (CHART D-3)

- SUMMARY OF DIFFERENCES

CHARACTERISTIC	51B	51F
ASSEMBLY TIME	MAY/JUNE	NOVEMBER
CLEANING CLOTH	RYMPLECLOTH	TEXWIPE
LEAK CHECK	100 PSIG	200 PSIG

- CONCLUSIONS
  - NO CORRELATION BETWEEN TIME OF INSTALLATION AND O-RING EROSION
  - RYMPLECLOTH STRANDS HAVE BEEN FOUND IN JOINTS BEFORE. A RYMPLECLOTH THREAD COULD HAVE LEAD TO PRIMARY SEAL LEAKAGE
  - THE PUTTY COULD HAVE MASKED A PRIMARY SEAL LEAK AT 100 PSIG
  - NO DISCERNABLE METAL PART DIFFERENCES
  - NO O-RING ANOMALIES OR DIFFERENCES

Chart 128

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- SECTION A--PROBLEM DESCRIPTION
- SECTION B--COMPARISON WITH PAST HISTORY
- SECTION C--STS-51B NOZZLE JOINT EROSION SCENARIO
- SECTION D--COMPARISON OF AS-BUILT 51-B NOZZLE JOINTS WITH 51-F
- SECTION E--FLIGHT READINESS ASSESSMENT FOR STS-51F

Chart 129

FLIGHT READINESS ASSESSMENT FOR STS-51F (CHART E-1)

- NOZZLE PRIMARY O-RING ON STS-51B (SRM-16A) DID NOT SEAL
- ANALYTICAL RESULTS SUPPORT OBSERVED EROSION SCENARIO IN SRM-16A AND INDICATE A WORST CASE EROSION CONDITION WHICH WOULD NOT ERODE SECONDARY O-RING BEYOND ITS SEALING CAPABILITY
- TESTS CONDUCTED VERIFYING VACUUM PUTTY CAN MASK 100 PSIG LEAK CHECK AND ALSO VERIFYING THAT SEAL WILL BE MAINTAINED WITH PREDICTED WORST CASE SECONDARY O-RING EROSION
- TEST CONDUCTED AT 200 PSIG VERIFY THAT VACUUM PUTTY CANNOT MASK 200 PSIG LEAK CHECK
- STS-51F (SRM-19) HAD 200 PSIG LEAK CHECK AND THEREFORE SHOULD EXHIBIT BEHAVIOR MORE LIKE STS-51D (SRM-17) AND STS-51G (SRM-18) WHICH EXHIBITED PRIMARY O-RING EROSION WHICH WAS WITHIN EXPERIENCE BASE WITH NO SECONDARY O-RING EROSION
- STS-51F (SRM-19) NOZZLE JOINTS ARE ACCEPTABLE FOR FLIGHT

Level I (July 2, 1985)

Chart 130

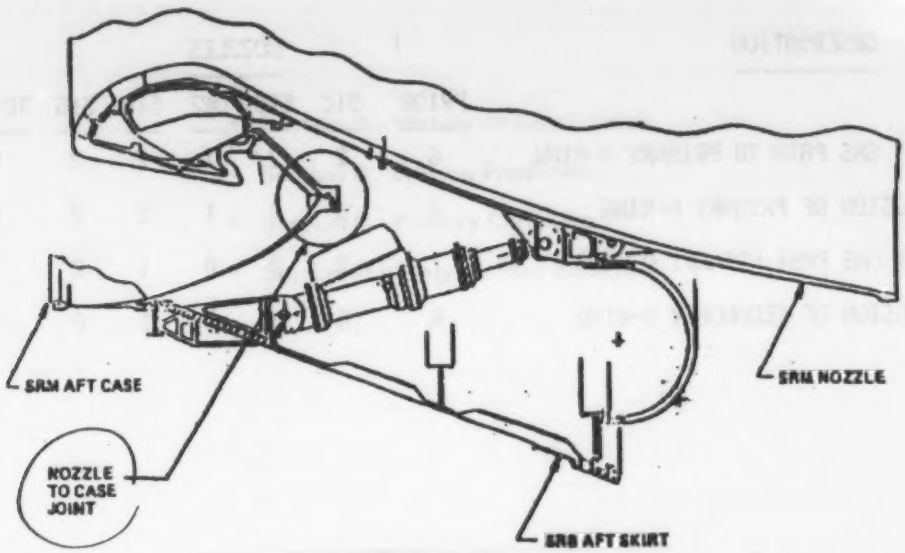
PROBLEM SUMMARY

PROBLEM	CONCERN	RESOLUTION	STATUS
UNUSUAL EROSION OBSERVED ON PRIMARY AND SECONDARY O-RINGS OF STS 51-B NOZZLE TO CASE JOINT (SRM 16 A) — PRIMARY O-RING APPARENTLY NEVER SEATED RESULTING IN WORST EROSION YET OBSERVED — SECONDARY O-RING HAD 32 MILS EROSION (1ST TIME OBSERVATION)	FLIGHT SAFETY	• EVIDENCE OF HOT GAS PAST PRIMARY O-RING IS NOT UNPRECEDENTED • LEAK CHECK USED ON STS 51-B DID NOT VERIFY CAPABILITY OF PRIMARY O-RING TO SEAL • LEAK CHECK USING 200 PSIG STABILIZATION PRESSURE ON STS 51-F AND SUBS PROVIDES CONFIDENCE THAT PRIMARY O-RINGS HAVE CAPABILITY TO SEAL • LEAK CHECK ASSURES SECONDARY O-RING WILL SEAL AGAINST MOTOR PRESSURE • MAXIMUM EROSION THAT CAN OCCUR ON SECONDARY O-RING IN LIMITED TIME THAT FLOW EXISTS ON AND PAST PRIMARY O-RING IS 75 MILS (CONSERVATIVE ANALYSIS) • —2 SUBSCALE TESTS VERIFY THAT A PROPERLY SEATED O-RING CAN SUSTAIN A MINIMUM OF 125 MILS EROSION BEFORE SEAL IS COMPROMISED	CLOSED

SRB-5

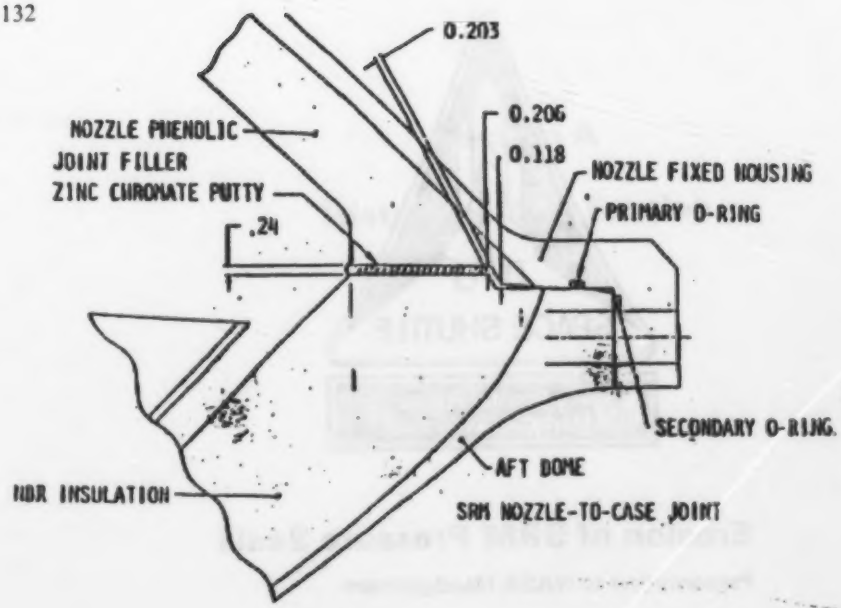
Chart 131

NOZZLE GEOMETRY



SRB 6

Chart 132



SRM NOZZLE TO CASE JOINT

Chart 133

HISTORY OF NOZZLE O-RING DAMAGE

OBSERVATION	NOZZLES						
	PRIOR	51C	51D	DM7	51B	51G	TOTAL
HOT GAS PATH TO PRIMARY O-RING	6	2	2	1	2	2	15
EROSION OF PRIMARY O-RING	4	0	2	1	2	2	11
HOT GAS PAST PRIMARY O-RING	1	2	0	0	1	2	6
EROSION OF SECONDARY O-RING	0	0	0	0	1	0	1

SRB-8

AUGUST 19, 1985 THIOKOL BRIEFING TO NASA HEADQUARTERS: Charts 134-189

Chart 134

SPACE SHUTTLE

Space Booster Programs
Morton Thiokol, Inc.

Erosion of SRM Pressure Seals

Presentation to NASA Headquarters

19 August 1985

Publication No. 87110

Chart 135

Agenda

- **Section A - History of Seal Erosion**
- **Section B - Erosion Predictions**
- **Section C - Primary Concerns**
- **Section D - Program Plan Summary**

Chart 136

Section A

History of Seal Erosion

Chart 137

Erosion Scenario

- Gas jet penetrates vacuum putty and impinges on primary seal
- Seal erosion continues until pressure in cavity between seal and putty equals motor chamber pressure

- Observed erosion
  - Primary seal erosion observed in 5 field joints, 12 nozzle joints, and 1 igniter joint
  - Periodic soot blowby past the primary seal has been observed in all joints
  - Primary seal has been compromised twice
    - DM-6 inner Gask-O-Seal on the igniter adapter
    - STS-51B (SRM-16A) nozzle-to-case joint

Chart 138

Space Shuttle SRM Joints

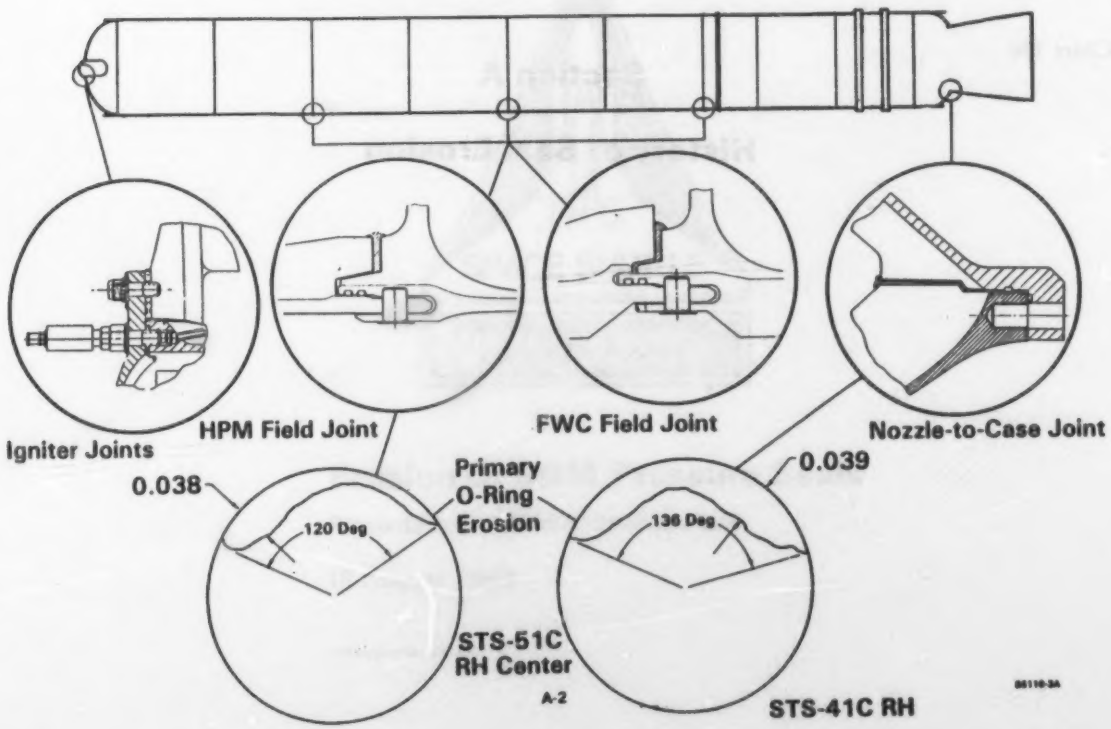


Chart 139

History of Field Joint

- 146 in. diameter
- Gap size from 0.01 to 0.40 in., length = 3.3 in.
- Gap filled with zinc chromate putty
- Putty on flight motors filled with asbestos
- O-rings leak checked through port between seals at 0 deg
- 5 of 111 joints have exhibited primary O-ring erosion (4.5%)

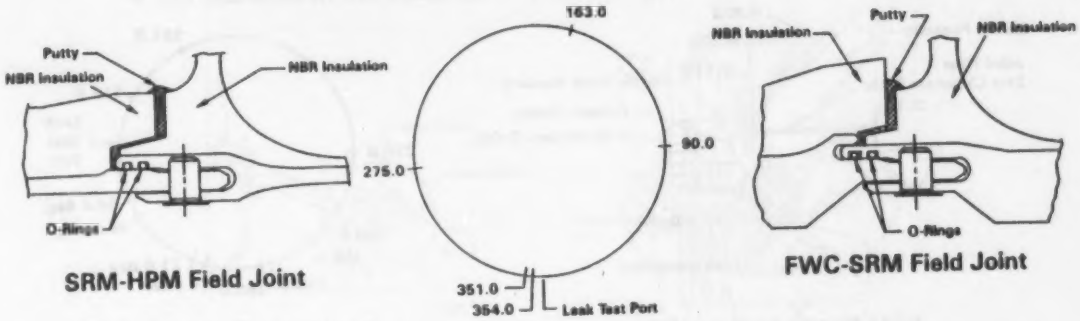


Chart 140

History of O-Ring Damage on SRM Field Joints

		Cross-Sectional View			Top View		
	SRM No.	Erosion Depth (in.)	Perimeter Affected (deg)	Nominal Dia (in.)	Length of Max Erosion (in.)	Total Heat Affected Length (in.)	Clocking Location (deg)
51C LH Forward Field**	15A	0.010	154.0	0.280	4.25	5.25	163
51C RH Center Field (prim)***	15B	0.038	130.0	0.280	12.50	58.75	354
51C RH Center Field (sec)***	15B	None	45.0	0.280	None	29.50	354
41D RH Forward Field	13B	0.028	110.0	0.280	3.00	None	275
41C LH Aft Field*	11A	None	None	0.280	None	None	--
41B LH Forward Field	10A	0.040	217.0	0.280	3.00	14.50	351
STS-2 RH Aft Field	2B	0.053	116.0	0.280	--	--	90

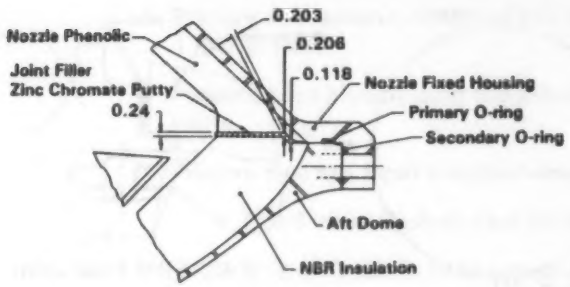
*Hot gas path detected in putty. Indication of heat on O-ring, but no damage
**Soot behind primary O-ring
***Soot behind primary O-ring, heat affected secondary O-ring

Clocking location of leak check port - 0 deg

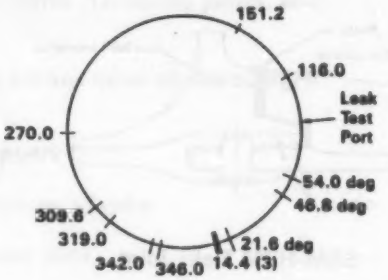
Chart 141

History of Nozzle-to-Case Joint

- 103 in. diameter
- Gap size from 0.005 to 0.34 in., length = 6.8 in.
- Gap filled with zinc chromate putty
- Putty filled with asbestos
- O-rings leak checked through port between seals at 91.8 deg
- 12 of 47 joints have exhibited primary O-ring erosion (25.5%)



SRM Nozzle-to-Case Joint



Clocking of Eroded O-rings

Chart 142

History of O-Ring Damage on SRM Nozzles

		Cross-Sectional View			Top View		
	SRM No.	Erosion Depth (in.)	Perimeter Affected (deg)	Nominal Dia (in.)	Length of Max Erosion (in.)	Total Heat Affected Length (in.)	Clocking Location (deg)
51F RH Nozzle*	19B	None	None	0.275	None	8.00	21.6
51G LH Nozzle**	18A	0.013	62.0	0.275	1.12	5.00	151.2
51G RH Nozzle**	18B	0.023	226.0	0.275	0.88	7.00	342.0
51G RH Nozzle**	18B	0.009	98.5	0.275	2.00	10.00	270.0
51B LH Nozzle (prim)***	16A	0.171	360.0	0.275	1.59	12.00	54.0
51B LH Nozzle (sec)***	16A	0.032	73.5	0.275	3.10	3.10	54.0
51B RH Nozzle	16B	0.005	124.0	0.275	3.40	4.70	14.4
DM-7 Nozzle	DM-7	0.088	246.5	0.275	12.00	34.00	46.8
51D LH Nozzle	17A	0.011	63.0	0.275	2.12	5.85	14.4
51D RH Nozzle	17B	0.068	126.0	0.275	6.00	11.00	116.0
51C LH Nozzle**	15A	None	None	0.275	None	None	109.0
51C RH Nozzle**	15B	None	None	0.275	None	None	63.0
41D LH Nozzle**	13A	0.046	121.0	0.275	4.00	7.00	309.8
41C RH Nozzle	11B	0.034	138.0	0.275	1.80	5.80	319.0
41B RH Nozzle	10B	0.039	103.5	0.275	0.75	45.00	14.4
QM-4 Nozzle	QM-4	0.051	101.0	0.275	5.00	11.00	346.0
STS-6 LH Nozzle*	6A	None	None	0.275	None	None	318.2
STS-6 RH Nozzle*	6B	None	None	0.275	None	None	251.0

*Hot gas path detected in putty, indication of heat on O-ring, but no damage
**Soot behind primary O-ring
***Soot behind primary O-ring, heat affected secondary O-ring

Clocking location of leak check port - 91.8 deg

Chart 143

History of Igniter Joints

- 20 in. diameter
- Gap size from 0.005 to 0.065 in., length = 3 in.
- Gap filled with zinc chromate putty
- Putty filled with asbestos
- Gaskets leak checked though port between seals at 305 deg and 338 deg
- 1 of 47 inner gaskets have experienced primary seal erosion (2.1%)
- No seal erosion has occurred on the outer gasket in 47 firings

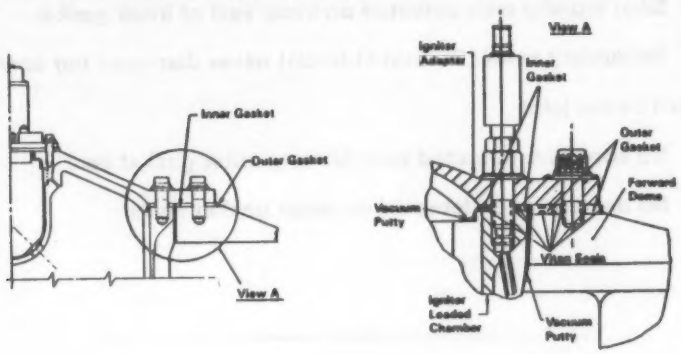


Chart 144

Summary of Significant Observations

- All joints
  - Seal damage always has associated putty blowhole
  - Putty blowholes exist without resultant seal damage
  - Soot blowby can occur away from a putty blowhole
  - Frequency of O-ring damage has increased since incorporation of
    - Randolph putty
    - Higher stabilization pressures in leak test procedure
    - High performance motors
  - Randolph putty is more susceptible to environmental conditions such as humidity and temperature
    - Can become leathery in dry conditions
    - Becomes extremely sticky in moist conditions and in some cases begins to disintegrate

Chart 145

- Igniter-to-adapter joint
  - Seal damage detected on DM-6 inner gasket
  - Soot blowby detected on
    - DM-6, STS-41C (RH), STS-41D (RH), STS-51D (LH), STS-51D (RH), STS-51G (LH)
  - Soot blowby only detected on inner seal of inner gasket
  - Secondary seals (36 Stat-O-Seals) never damaged nor compromised
- Igniter-to-case joint
  - No soot ever detected past primary outer gasket seal
  - No damage ever detected on outer gasket seals

Chart 146

Summary of Significant Observations (Cont)

- Field joints and nozzle-to-case joint
  - 200 psig pressurization is required to prevent the putty from masking a potential leak in the primary O-ring
    - This can occur when the joint gap is toward minimum side
  - Putty blowholes can be created by air entrapment during assembly
  - Putty blowholes can be created during a successful leak test
  - Putty blowholes can be created during ignition
- Igniter adapter-to-chamber joint
  - Inner gaskets with a rubber overfill condition are always present when seal damage or soot blowby occurs
  - Inner gaskets with a rubber overfill condition do not always lead to seal damage or soot blowby
  - Outer gasket has never exhibited erosion of the primary seal

Chart 147

Section B
Erosion Predictions

Chart 148

Analytical Modeling of Pressurization/Erosion of SRM O-Rings

- A volume-filling (lumped parameter) model for the pressurization of the cavity ahead of the primary O-ring was constructed
- A model was added for stagnation-point heat transfer during jet impingement (Shadlesky, AIAAJ, 8.83)
- Experimental data identified the resulting erosion rate for Viton O-rings
- This model was automated as computer program ORING
- ORING was validated in four ways (TWR-14952):
    - Comparison to idealized pressurization where exact solution exits
    - Agreement with approximate closed-form model
    - Accurate simulation of 27 hot subscale tests
    - Application to SRB field joints and nozzle joints to show that predictions are consistent with measured erosion data
- The analysis shows that erosion increases with difficulty of filling; increasing cavity volume and heat loss and decreasing jet area
- The approximate closed-form solution allows quantitative trade-off estimates to be made to verify and explain the effect of these parameters